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IMPROVEMENT OF SHOCK MEASUREMENTS FOR ARMORED VEHICLES - ILIR T--ETC(U)
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JANUARY 1979

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A study was conducted at Aberdeen Proving Ground from April to September 1978. Data from piezoelectric and piezoresistive accelerometers subjected to short duration shocks were analyzed. Various configurations and materials were used to mechanically filter out high-frequency acceleration. Electrical filtering of the accelerometer signal before recording was preferable to the soft mounts made for this project, because the electrical filters had much more damping. Newly introduced, commercially fabricated soft mounts have been ordered and will be tested when they are received. For short-duration Cont

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20. shocks the best measurements were obtained with piezoresistive (strain-gage) type accelerometers with filtering. The worst measurements were obtained with piezoelectric (crystal) type accelerometers and no filtering. The most reasonable interpretation was obtained by comparing velocity changes (integral of the acceleration). The worst interpretation was obtained by comparing peak accelerations.

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FOREWORD

The Materiel Testing Directorate, Aberdeen Proving Ground (APG), MD was responsible for preparing the proposal, conducting this investigation, and writing this report. Funds for this study were provided by the In-House Laboratory Independent Research Program (ILIR).

The encouragement and interest in this program received from Mr. Cecil Martin, project engineer for XM1 vulnerability testing, is gratefully acknowledged. W. Scott Walton conducted the investigation and prepared this report.

SECTION 1. SUMMARY

1.1 BACKGROUND

Acceleration is one of the chief measurements made during ballistic impact tests. A typical test will consist of 5 to 20 shots fired into a vehicle instrumented with 18 to 48 piezoelectric accelerometers. In the past, as much as a third of the data is lost due to DC offset or accelerometer breakage.

Because of the imminent testing of the XM1, APG has contacted several agencies, including Sandia Laboratories, the Shock and Vibration Information Center, Frankford Arsenal, Endevco, Naval Ordnance Laboratories, and the National Bureau of Standards in an effort to improve ballistic shock-measurement techniques. From these discussions it was found that little work has been published on shock levels as high (100,000 g's) or as fast (less than 50 microseconds) as encountered in ballistic shock. This area has been described as a peculiar region where high-level accelerations are caused by high-velocity stress waves.

The damage potential of stress-wave-induced acceleration is not well defined, but it is generally felt that even though the acceleration levels are high, the velocity change and damage potential are small. Transducer mounting conditions such a surface finish, flatness, and mounting torque cause large variations in results and differences of more than $\pm 50\%$ are typical.

Because of the problems encountered in high-level shock, the National Bureau of Standards does not calibrate accelerometers above 10,000 g's. The calibration of accelerometers for the shock values encountered in ballistic impact is therefore done indirectly or at levels at least one order of magnitude below the level of interest.

Preliminary research indicated that many of the problems in ballistic shock measurement might be eliminated by using piezoresistive accelerometers mounted so they are isolated from the high-frequency acceleration caused by stress waves. This "mechanical filtering" will allow lower frequency acceleration components (with higher velocity change and damage potential) to fall within the signal-to-noise ratio of the tape recorder or digital memory used to store the shock record. This study was conducted to determine if these solutions were satisfactory both from an accuracy and a field usability standpoint.

1.2 OBJECTIVES

The objectives of this study were:

a. To compare piezoelectric (crystal) and piezoresistive (strain-gage) accelerometers.

b. To try various soft-mounting techniques to mechanically filter out high-frequency acceleration.

c. To assist in the gathering and analysis of ballistic shock data taken under field testing conditions.

1.3 SUMMARY OF PROCEDURES

Laboratory and field tests were conducted using both piezoelectric (crystal) and piezoresistive (strain-gage) accelerometers and the results were compared. Various configurations and materials were used to mechanically filter out high-frequency acceleration.

Field data from four tests were gathered and analyzed. Only one of these tests involved ballistic impact; the other three were large-caliber weapon firings. The recoil shock of a large-caliber weapon is significantly different from the ballistic impact shock because of the large amount of rigid body motion during recoil. Also present during recoil shock, however, are high-frequency transients that ring accelerometers at their own natural frequencies. Since weapons are often instrumented with displacement-measuring equipment, a good understanding of the rigid body motion is available. With this understanding, accelerometer signals can be analyzed and those that are realistic can be separated from those that are physically impossible.

1.4 SUMMARY OF RESULTS

The best measurements under field test conditions were obtained using piezoresistive accelerometers and filtering; the worst measurements were obtained using piezoelectric accelerometers and no filtering. The most meaningful interpretation of the data came from comparing the peak velocity changes; the least meaningful interpretation came from comparing the peak accelerations.

The soft mounting techniques used in this study resulted in the introduction of a new, underdamped resonance that was objectionable when compared with electronic filtering. Newly introduced, commercially fabricated soft mounts have been ordered and will be tested when they are received.

1.5 ANALYSIS

A typical ballistic shock record is in figure 1.5-1. It shows high-frequency ringing ($\sim$ 20 kHz) well above the usable frequency range of the accelerometer ($\sim$ 9 kHz). Little useful information is available from this presentation of the data. A poor way of interpreting the data is to pick the largest "whisker" ($\sim$ 12,000 g's) and simply state that at this location 12,000 g's are present, thereby implying that objects in this position should be designed to withstand 12,000 times their own weight!

1.5(Cont'd)

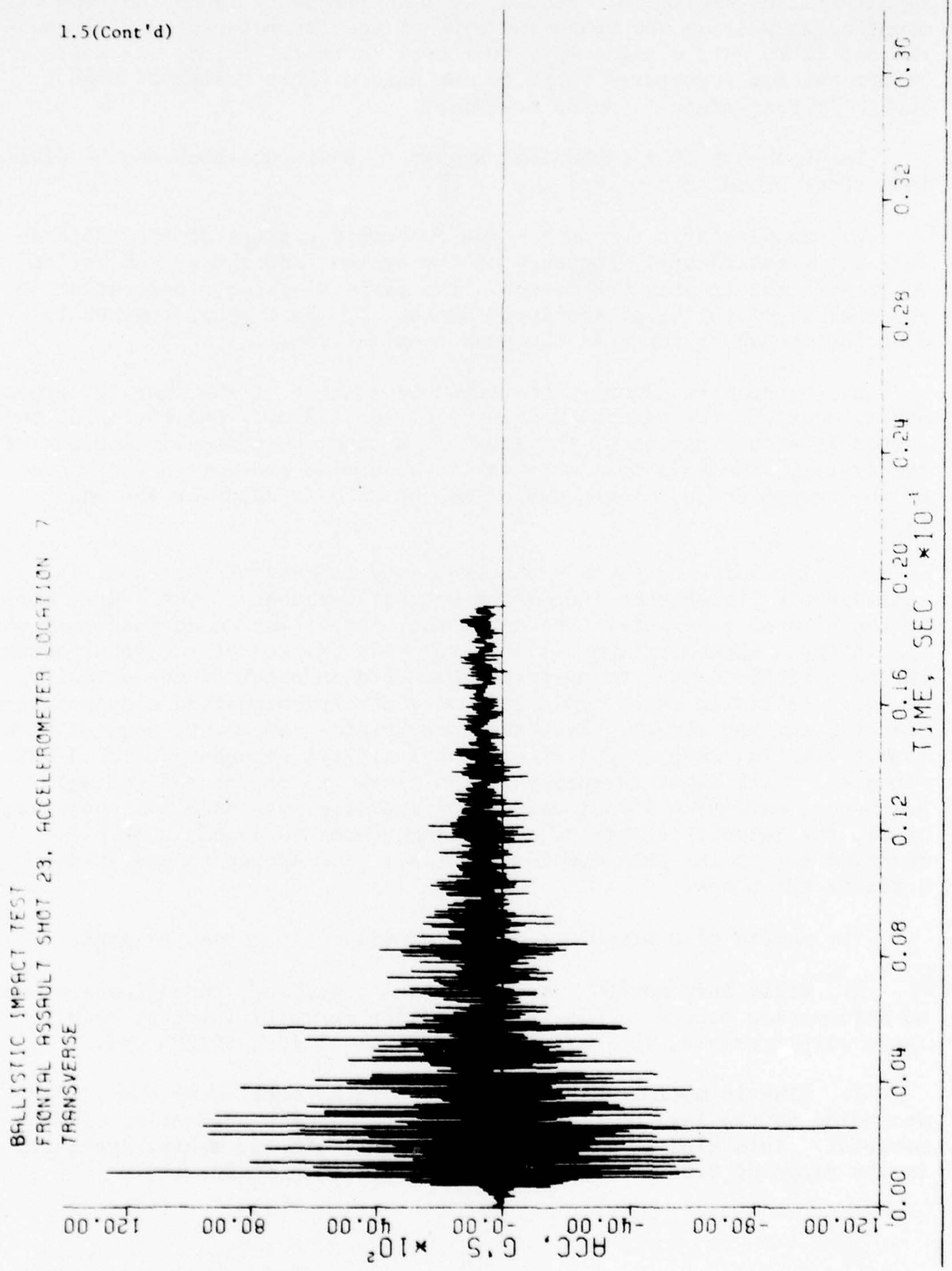


Figure 1.5-1. Typical ballistic shock record.

1.5 Cont'd)

There are several errors in this interpretation. First, the frequency range of the signal is well above the useful frequency range of the accelerometer, which for an undamped accelerometer means that the signal will be amplified. Second, in this frequency range the type of mounting as well as the brand and type of accelerometer used will cause the result to vary considerably from test to test. Third, and most important, few structures known to man have a first resonance high enough to respond to a 20-kHz transient.

The response of a mechanical system to an input shock can be divided into three broad categories:

a. Quasi-static response - the frequency content of the shock is well below the natural frequency of the system, and the system motion duplicates the input shock motion. The maximum system acceleration is the peak acceleration of the input shock. The best single number to describe the shock input is the peak acceleration.

b. Dynamic response - the frequency content of the shock is approximately equal to the natural frequency of the system. The motion of the system is a combination of the shock input and the natural resonance of the system. There is no simple way to determine the motion (response) of the system and no single number can be used to describe the shock input.

c. Impulsive response - the frequency content of the shock is considerably higher than the system natural frequency. The system motion is the natural resonance. The amplitude of this motion depends only on the integral (acceleration x time = velocity change) of the input shock. The best single number to describe this kind of shock is the velocity change. Ballistic shock typically contains very-high-frequency acceleration (20 kHz and above). Even the most "rigid" components mounted on a combat vehicle, such as gun sights, have a first resonance below 2 kHz. Since the shock input frequency is ten times the structure resonant frequency, ballistic impact causes an impulsive response in structures; hence, the velocity change of a ballistic shock is a good number to describe the shock--peak acceleration is a poor number to use in describing the shock.

The motion of a structure can be divided into three categories:

a. Rigid body motion - the structure translates through space and no deformation occurs. This type of motion normally involves fairly large displacements, typically greater than 0.1 inch (0.254 cm).

b. Elastic motion - the structure remains stationary, but deforms according to the laws of elasticity and the elastic properties of the material. This kind of motion involves small displacements, typically in the range of 0.01 inch (0.25 mm) to 0.001 inch (0.025 mm).

1.5 (Cont'd)

c. Surface motion - this motion is caused by stress waves traveling through the material. Distortion of the material depends on the acoustic properties of the material and is best described in terms of wave motion. This type of motion involves extremely small displacements, typically less than 0.000034 inch (1 micron).

During ballistic impact, stress waves containing a discontinuity (just as shock waves in air contain a pressure discontinuity) travel through the armorplate. As this discontinuity travels past an accelerometer, an instantaneous change in displacement occurs, resulting in an "infinite" acceleration. The accelerometer tries to respond at its own natural frequency, resulting in a "ring" at the accelerometer natural frequency.

Manufacturers of undamped accelerometers warn against using the accelerometer to measure acceleration with a pulse width below a specified value. During ballistic testing it is impossible to control the acceleration pulse width that will be present. "Soft mounting" is an attempt to control the pulse width experienced by the accelerometer regardless of the pulse width present on the plate.

If it were possible to provide damping in the accelerometers that measure high-level shock (10,000 to 100,000 g's), the accelerometer ringing problem could be eliminated and better measurements could be obtained. Unfortunately, because of the small displacements made by the seismic mass of the accelerometer, traditional oil or gas damping techniques are not practical.

The amplitude difference between rigid body motion (<100 g's) and surface motion (>10,000 g's) is so great that it is rare that both signals will fall within the signal-to-noise ratio of recording equipment. It must therefore be decided in advance which type of motion is important and appropriate filtering, mounting, and gain-adjustment steps must be taken before the signals are recorded.

The effect of stress-wave-induced acceleration on a structure varies greatly with the structure's mounting, number and type of joints, flatness, and surface finish because the displacements are so small. Only items with high natural frequencies (such as accelerometers) are affected significantly by this type of motion. For this reason it is usually desirable to avoid (by filtering or "soft mounting") recording stress-wave-induced acceleration.

In ballistic shock measurement, a typical decision might be to filter out surface motion but attempt to measure elastic motion. A typical filtering frequency for this approach might be 4 kHz. At a minimum, signals from undamped accelerometers should be low-pass filtered at the end of the accelerometer usable frequency range to prevent recording an accelerometer ringing at its own natural frequency.

1.5 (Cont'd)

In general, piezoresistive accelerometers have been more reliable, more consistent, and easier to work with than piezoelectric accelerometers. The excessive ring and DC shift characteristics of piezoelectric accelerometers are discussed elsewhere in this report. A problem not discussed elsewhere is the tendency of charge amplifiers to drift when cables are subjected to the wet and dirty conditions typical of field testing, or when moisture condenses within the electronics because the instrumentation trailer cools overnight. This problem causes delays in testing or the use of questionable techniques, such as offsetting the amplifier so it will be drifting through zero when the test round is fired.

Figure 1.5-2 illustrates a poor acceleration-measurement technique. Note that the peak acceleration in both channels is approximately 1000 g's, even though one accelerometer is mounted in the direction of fire and the other is perpendicular to the line of fire of the weapon. Obviously, using peak acceleration from these signals to describe the shock would be meaningless. The signal from channel 8 (perpendicular to the line of fire) consists almost entirely of oscillation at the natural frequency of the accelerometer. The velocity change is the most useful information available from the data and shows immediately which channel is in the line of fire (and receiving a significant shock) and which channel is perpendicular to the line of fire (receiving insignificant shock).

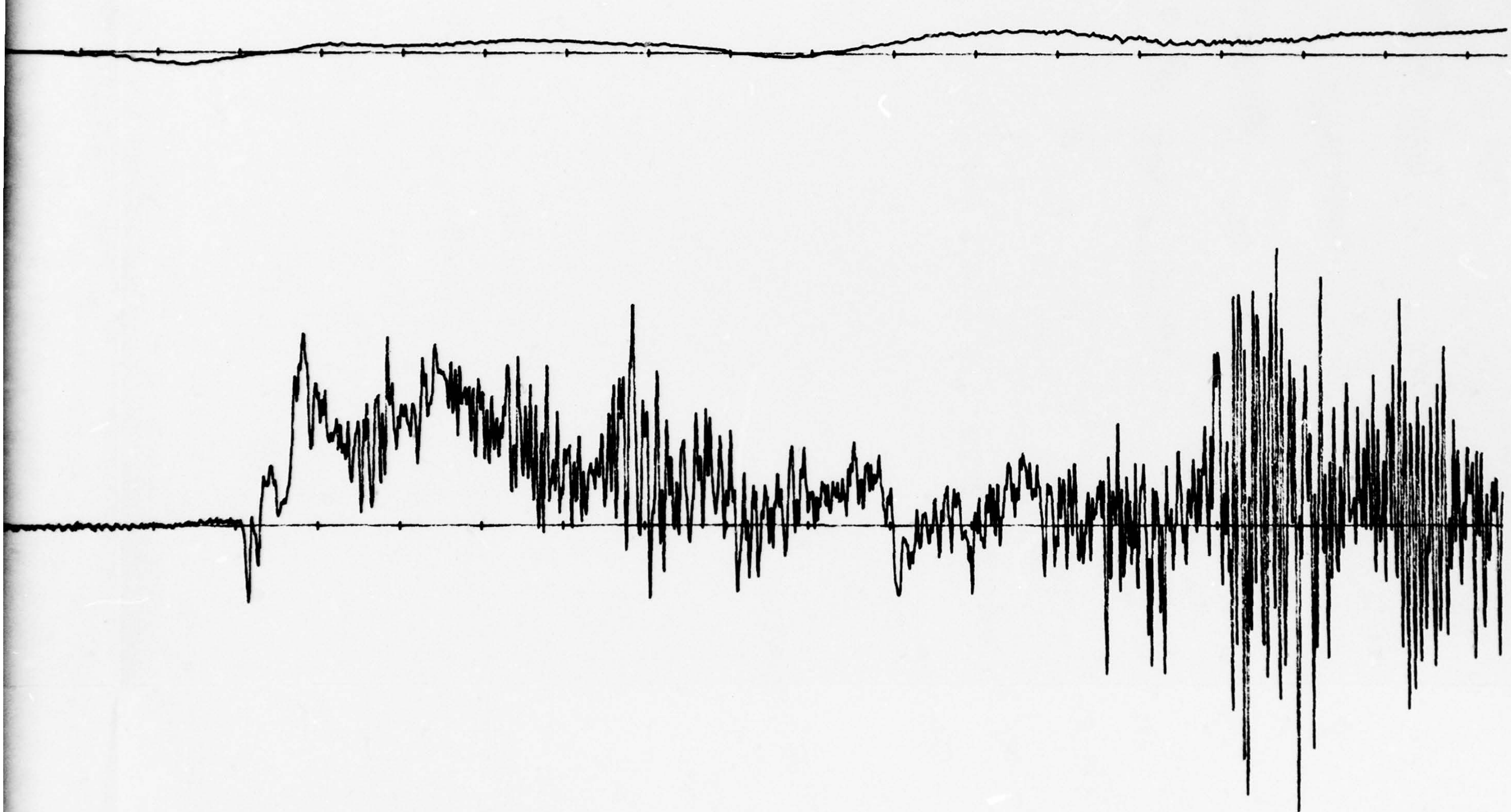
An example of much better acceleration-measurement technique is in figure 1.5-3 (page 10). Notice that the difference between a high-velocity round and a low-velocity round is immediately obvious from both the acceleration and the velocity change plots. Further evidence that the type of data shown in figure 1.5-3 is good includes: (1) three different accelerometers agreed to within 5% and (2) the velocity change indicated by the accelerometers agreed to within 3% of the recoil velocity recorded by displacement-measuring instrumentation.

Two significant points should be emphasized in the last three examples:

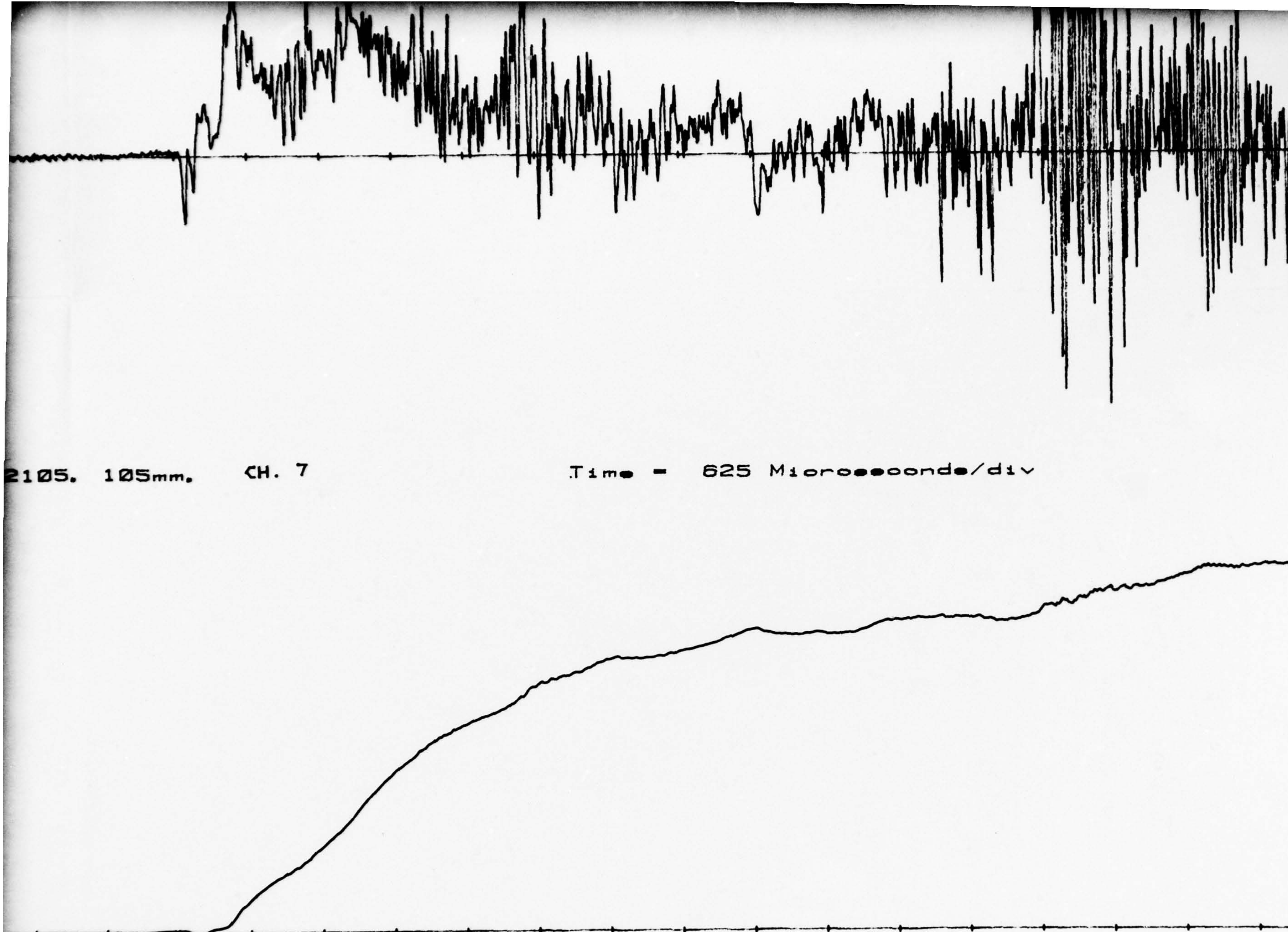
a. The best shock-measurement results were obtained using piezoresistive accelerometers and filtering. The worst results were obtained using piezoelectric accelerometers and no filtering.

b. The most meaningful interpretation of the data was obtained by comparing the peak velocity changes. The least meaningful interpretation was found by comparing the peak accelerations.

#2105. 105mm. Ch. 8 Time = 625 Microseconds/div

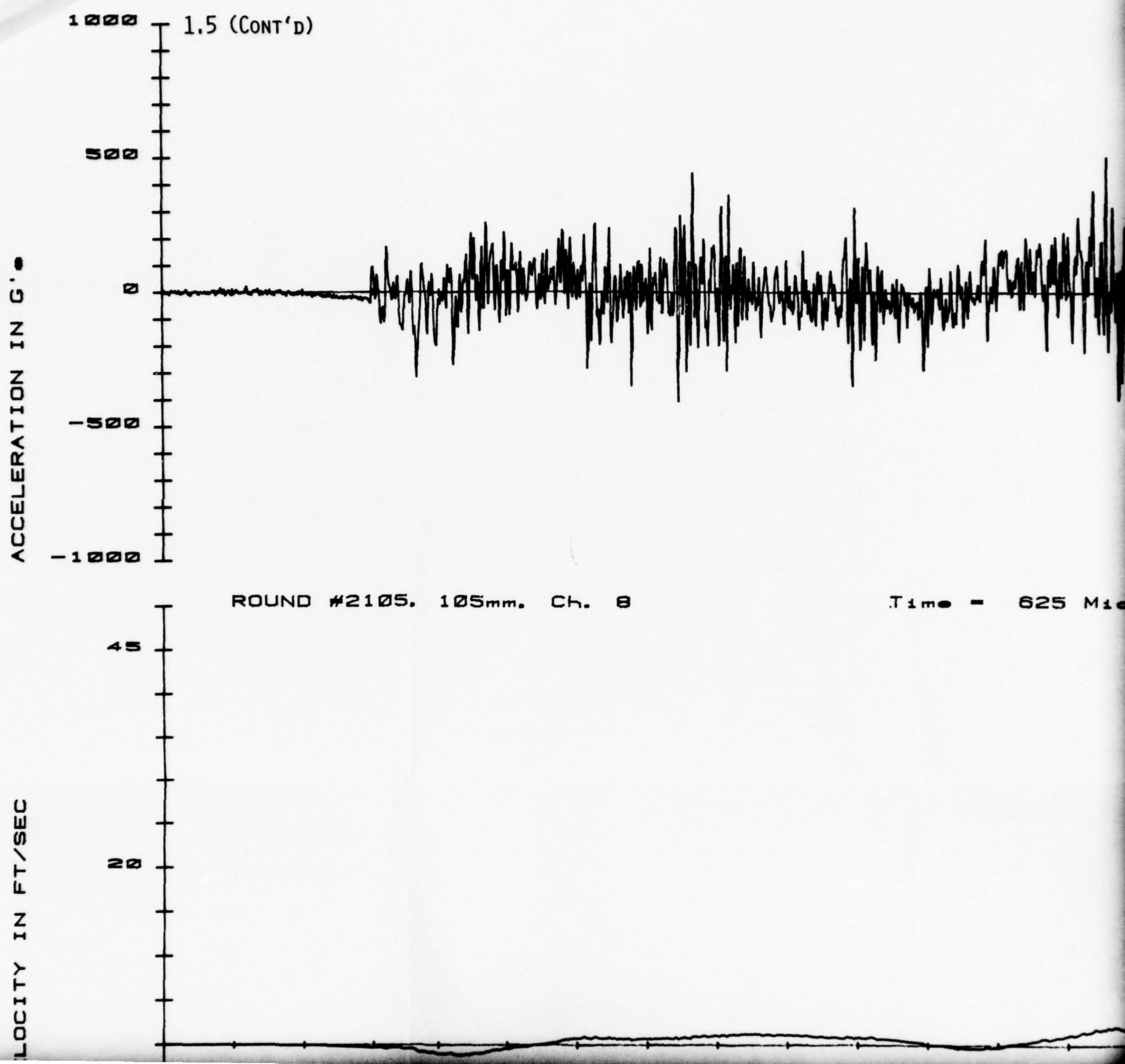


#2105. 105mm. CH. 7 Time = 625 Microseconds/div

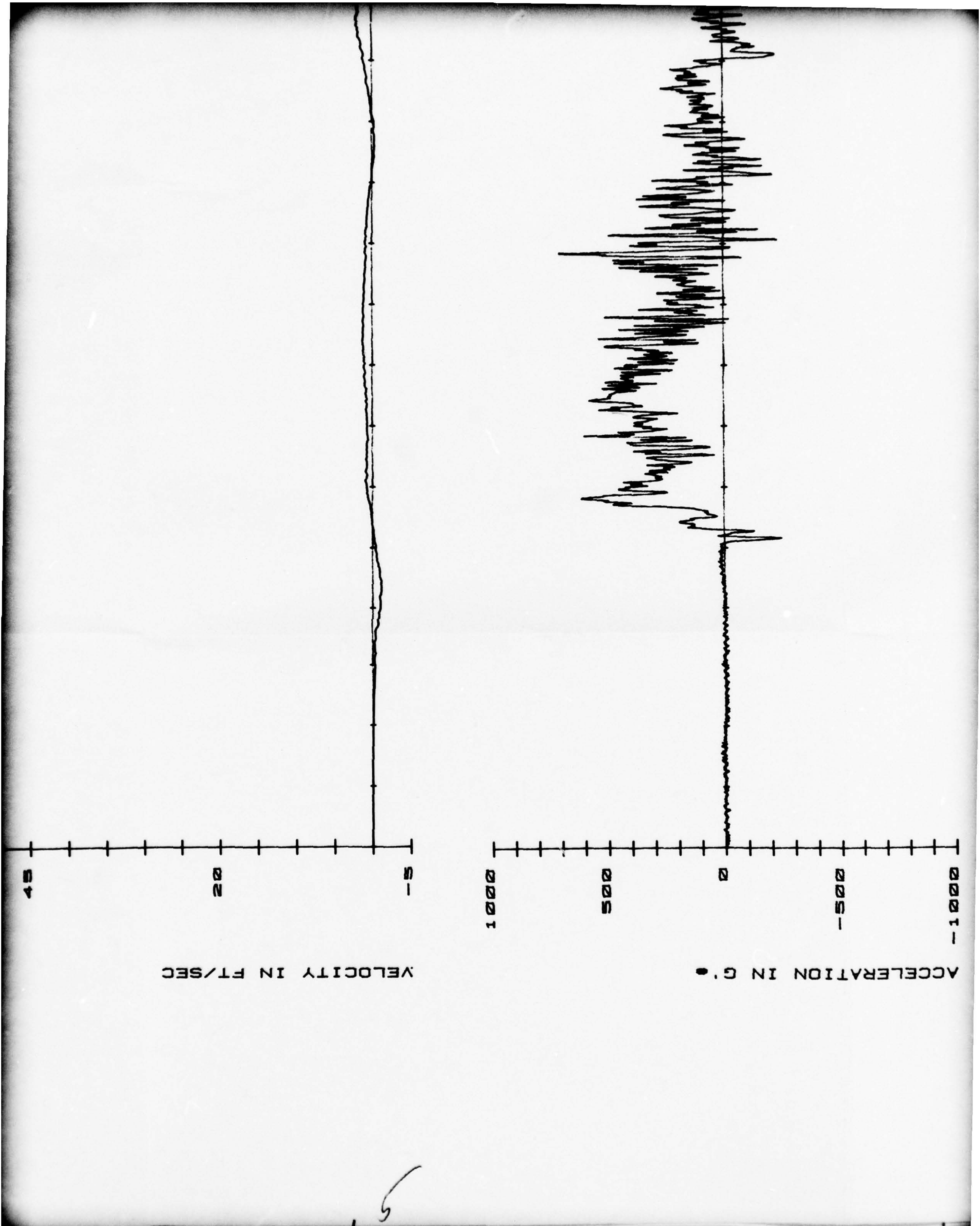


URE 1.5-2. ACCELERATION MEASURED ON A 105-MM HOWITZER USING PIEZOELECTRIC ACCELEROMETERS AND NO FILTERING. IS IN THE LINE OF FIRE AND CHANNEL 8 IS PERPENDICULAR TO THE LINE OF FIRE.

1.5 (CONT'D)


1000
500
0
-500
-1000
ACCELERATION IN G's
ROUND #2105. 105mm. Ch. 8
Time - 625 Mic
45
20
LOCITY IN FT/SEC

4


VELOCITY IN FT/SEC
45
20
-5
ACCELERATION IN G'S
1000
500
0
-500
-1000

5

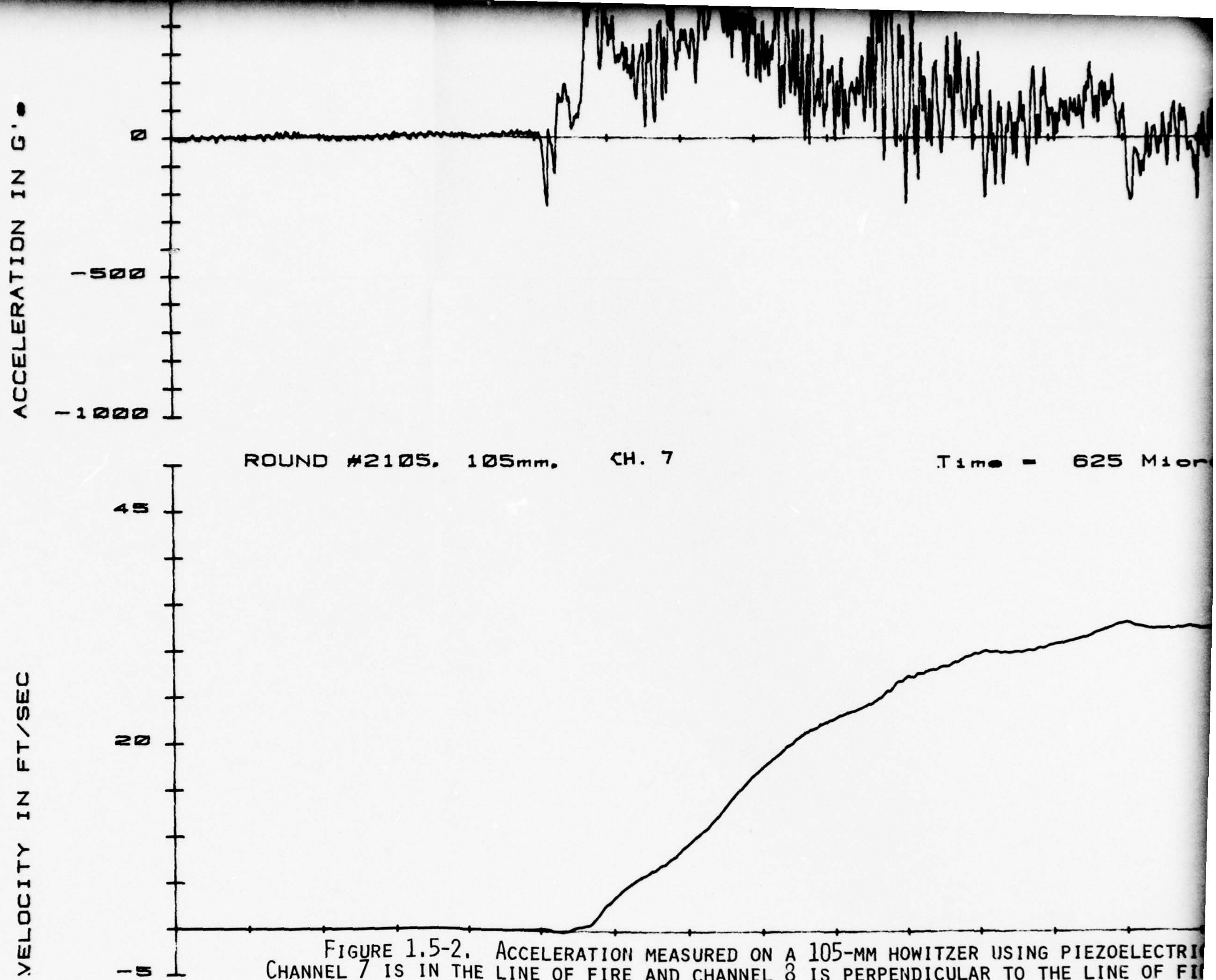
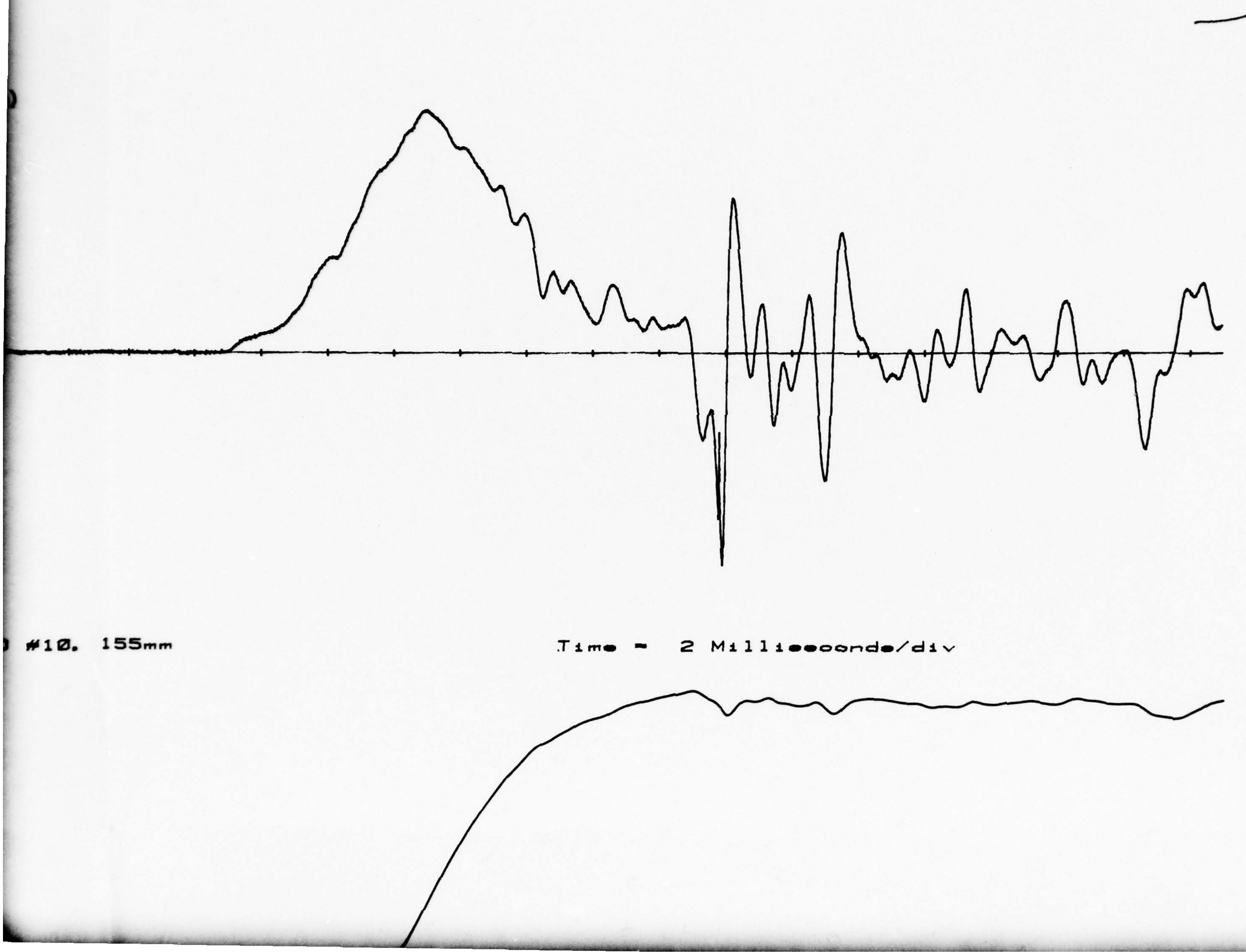
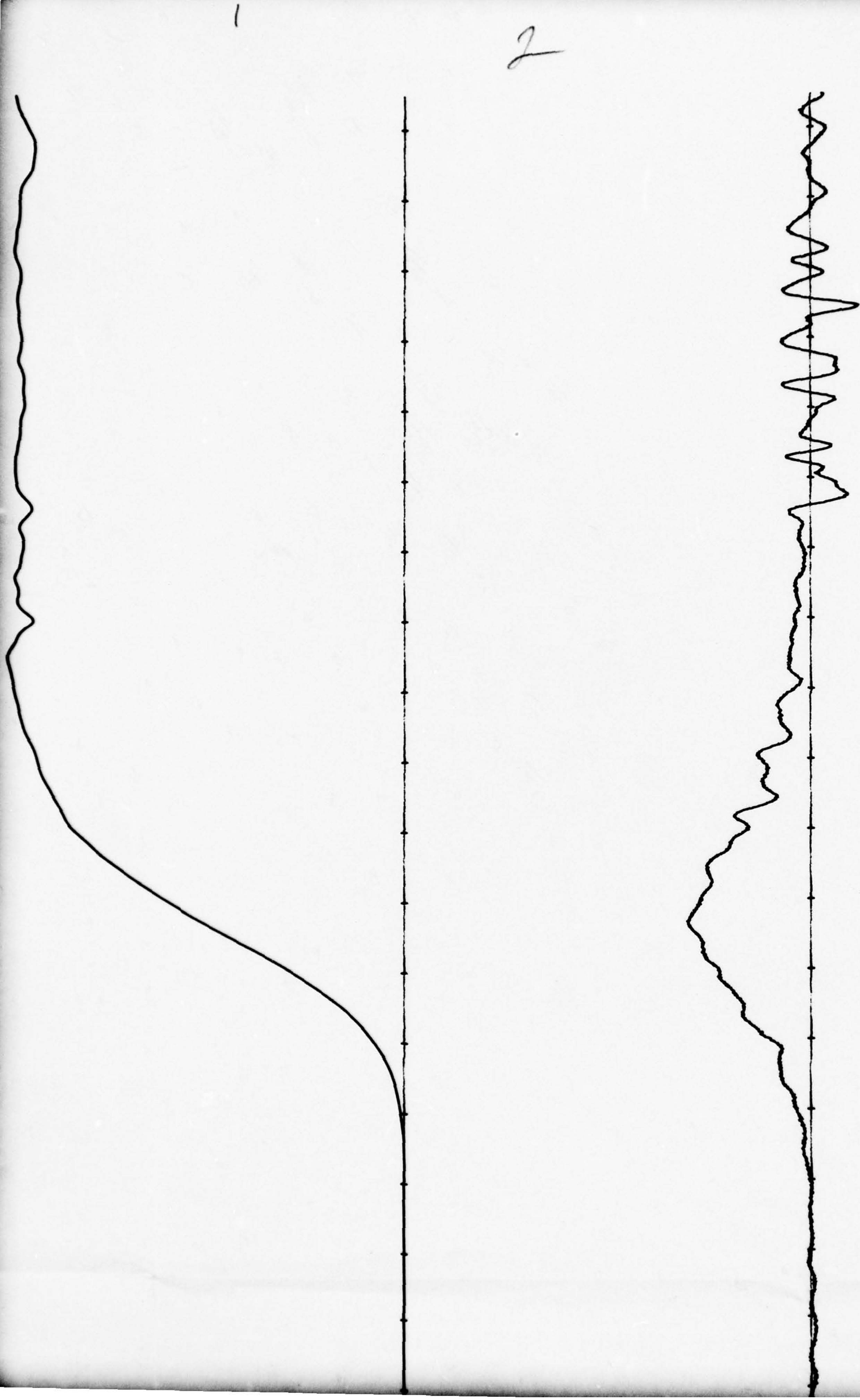
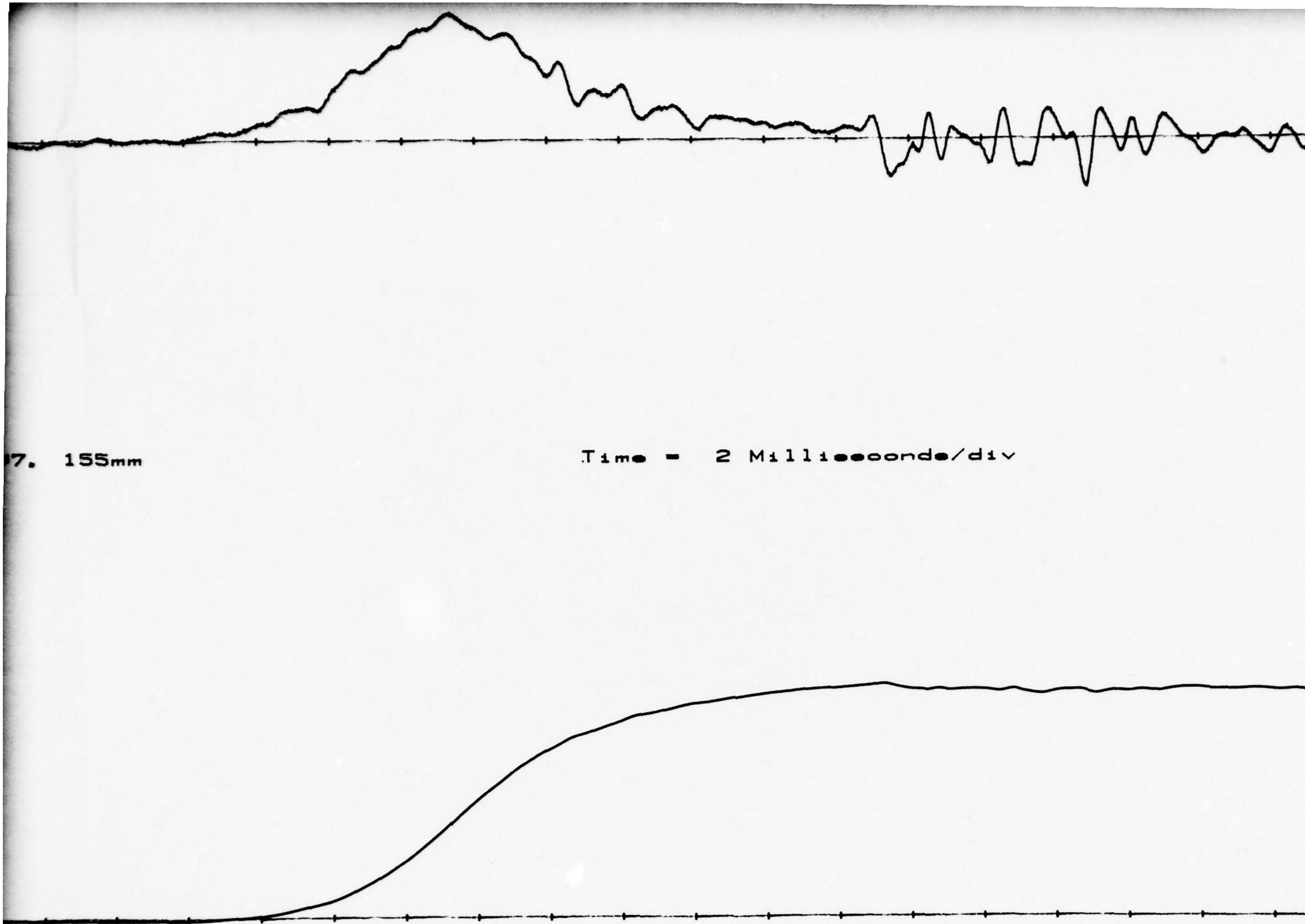


FIGURE 1.5-2. ACCELERATION MEASURED ON A 105-MM HOWITZER USING PIEZOELECTRI
CHANNEL 7 IS IN THE LINE OF FIRE AND CHANNEL 8 IS PERPENDICULAR TO THE LINE OF FI

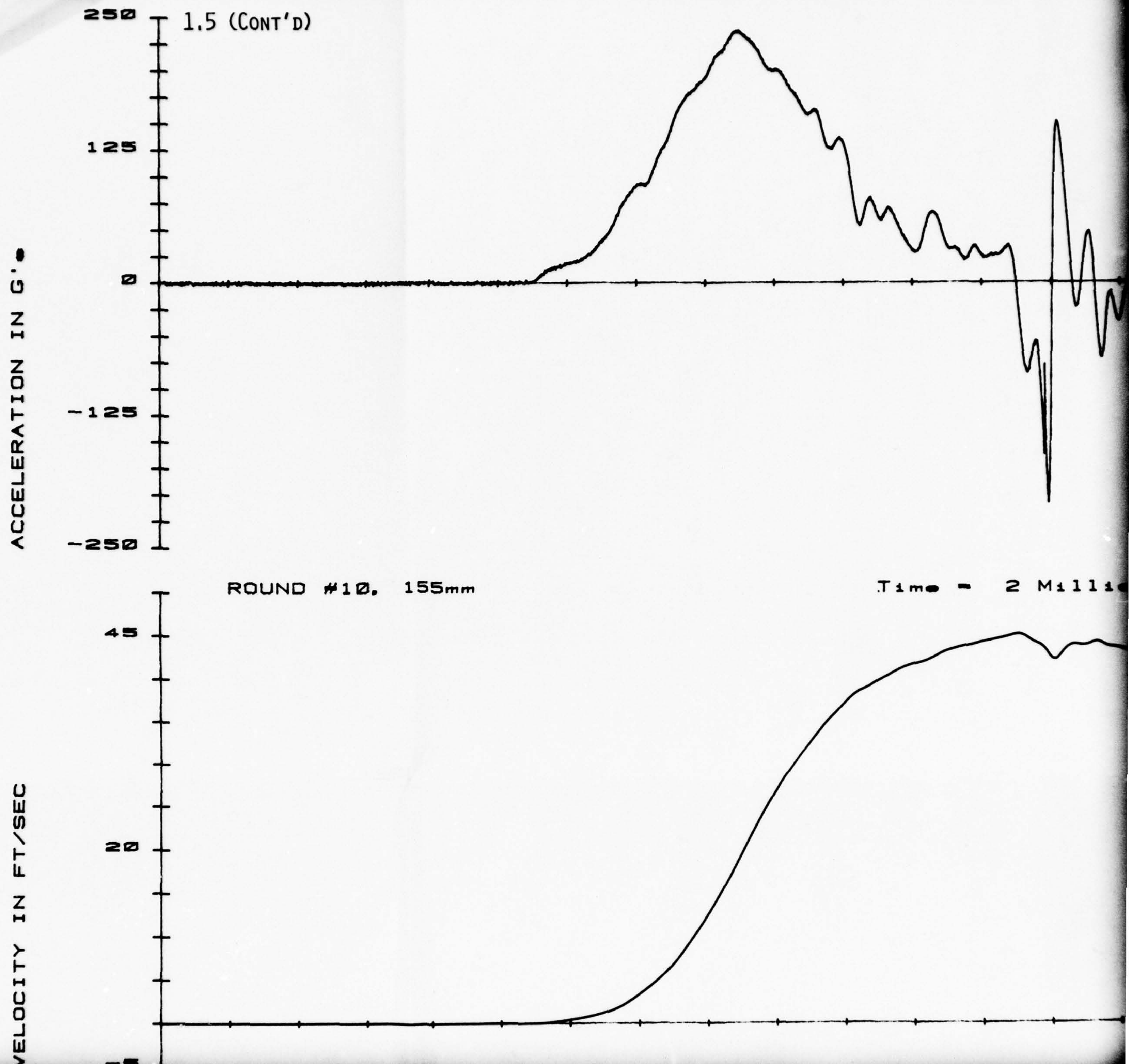

#10. 155mm
Time = 2 Milliseconds/div


1
2

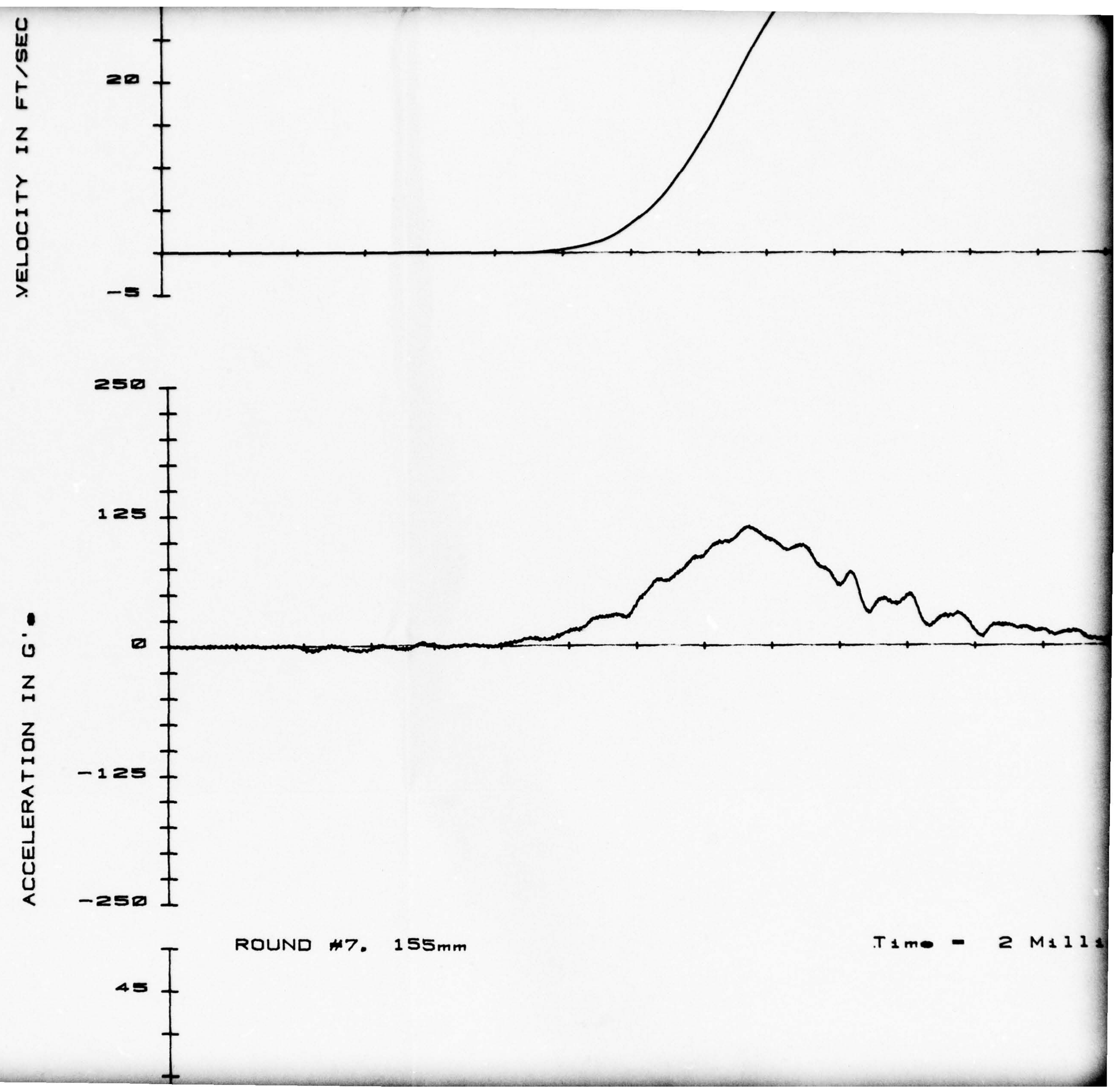


IGURE 1.5-3. ACCELERATION MEASURED ON A 155-MM HOWITZER USING PIEZORESISTIVE ACCELEROMETERS AND FILTERING
IZ. ROUND 10 IS A HIGH-VELOCITY (ZONE 8) SHOT AND ROUND 7 IS A LOWER-VELOCITY SHOT (ZONE 7).

W



1.5 (CONT'D)
ACCELERATION IN G'S
250
125
0
-125
-250
ROUND #10, 155mm
Time = 2 Milli
VELOCITY IN FT/SEC
45
20
-5


VELOCITY IN FT/SEC
20
-5
ACCELERATION IN G'S
250
125
0
-125
-250
45
ROUND #7. 155mm
Time = 2 Milli

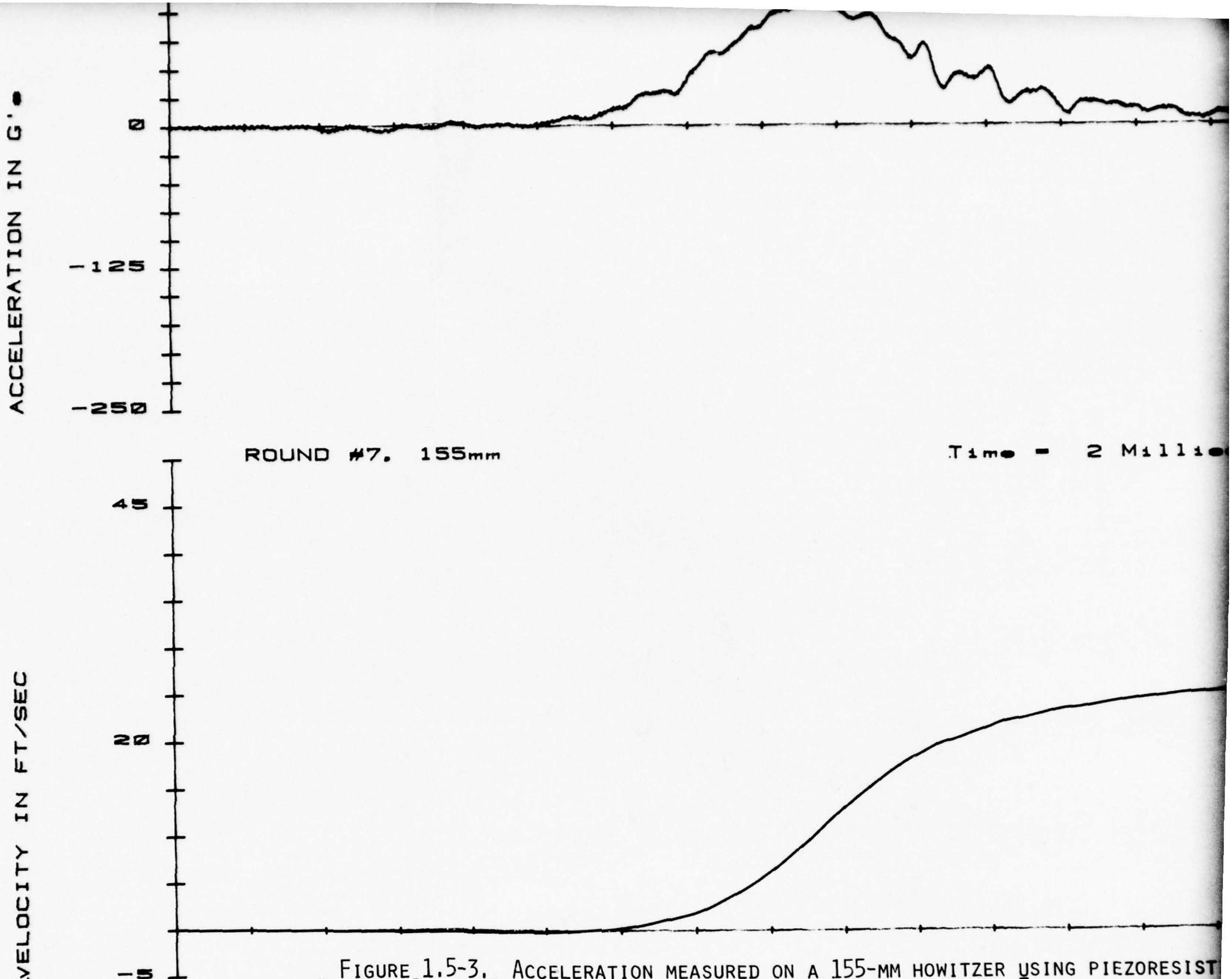


FIGURE 1.5-3. ACCELERATION MEASURED ON A 155-MM HOWITZER USING PIEZORESIST
AT 1 KHZ. ROUND 10 IS A HIGH-VELOCITY (ZONE 8) SHOT AND ROUND 7 IS A LOWER-VELO

6

1.6 CONCLUSIONS

a. Ballistic shock is an impulsive phenomena; therefore, techniques for measuring and analyzing an impulse should be used.

b. Depending on the mounting, filtering, and type of accelerometer used, almost any number can be obtained for peak acceleration during ballistic shock.

c. Peak acceleration is therefore an almost meaningless number in the evaluation of ballistic shock. Peak velocity change is a much more meaningful number to use in evaluating ballistic shock.

d. In controlled shocks where the pulse width of the shock is above a certain critical value, piezoelectric accelerometers agree quite well with piezoresistive accelerometers.

e. In ballistic shock, where pulse width cannot be controlled, piezoelectric (crystal) accelerometers with no filtering produce the worst results; piezoresistive (strain-gage) accelerometers with filtering produce the best results.

1.7 RECOMMENDATIONS

a. Piezoresistive accelerometers and filtering should be used when possible in the measurement of ballistic shock.

b. A computer program to determine velocity change from ballistic shock data is required and will be written by the MTD Analytical Laboratory to allow quick and efficient analysis of the great volume of data anticipated during the XM1 vulnerability testing.

c. TECOM TOP 2-2-620, Resistance of Armored Vehicles to Severe Shock, should be changed to incorporate these findings.

SECTION 2. DETAILS OF INVESTIGATION

2.1 FIELD TEST RESULTS

This section describes acceleration data taken under field testing conditions (i.e., outdoors, using cables 150 meters or longer, and recording data on FM magnetic tape). Data from four tests will be discussed:

a. Explosion of a landmine under a tank.

b. Firing of a 105-mm tank gun.

c. Firing of a 105-mm howitzer.

d. Firing of a 155-mm howitzer.

Landmine test - shown in figures 2.1-1 through 2.1-4 are four acceleration-versus-time shots taken from three different locations when a landmine exploded under a tank. All accelerometers were mounted in the same direction (vertical) on the hull floor, and were within a few inches of each other. One would expect that a similar shock was present at all locations. Note that DC shifts occurred in both piezoelectric accelerometers (figures 2.1-1 and 2.1-4). The peak acceleration value from the unfiltered piezoelectric accelerometer (figure 2.1-1) is approximately 9000 g's. The peak acceleration of the piezoelectric accelerometer filtered at 1 kHz (figure 2.1-4) shows a peak acceleration of approximately 14,000 g's! This result is almost certainly in error. The signal of this accelerometer was also to be recorded with filtering at 10 kHz, but it overdrove the tape-recorder electronics, which were adjusted to clip at about 14,000 g's. A quick "eyeball integration" of this plot (4000 g's, sustained for 7 milliseconds) reveals a velocity change of 902 feet/second (275 meters/second), which is inconceivable. In addition, since no negative acceleration is shown to reduce this velocity over the remaining 50 milliseconds, a displacement of 900 x 0.05 = 45 feet (13.7 meters) is implied. Obviously this channel is bad.

These four data channels illustrate several problems typical of ballistic shock:

a. Lack of agreement between accelerometers mounted in the same location.

b. Loss of data (or obviously bad data) on one accelerometer while accelerometers on either side provide believable results.

c. Lack of a meaningful, useful interpretation and presentation of the data.

2.1 (Cont'd)

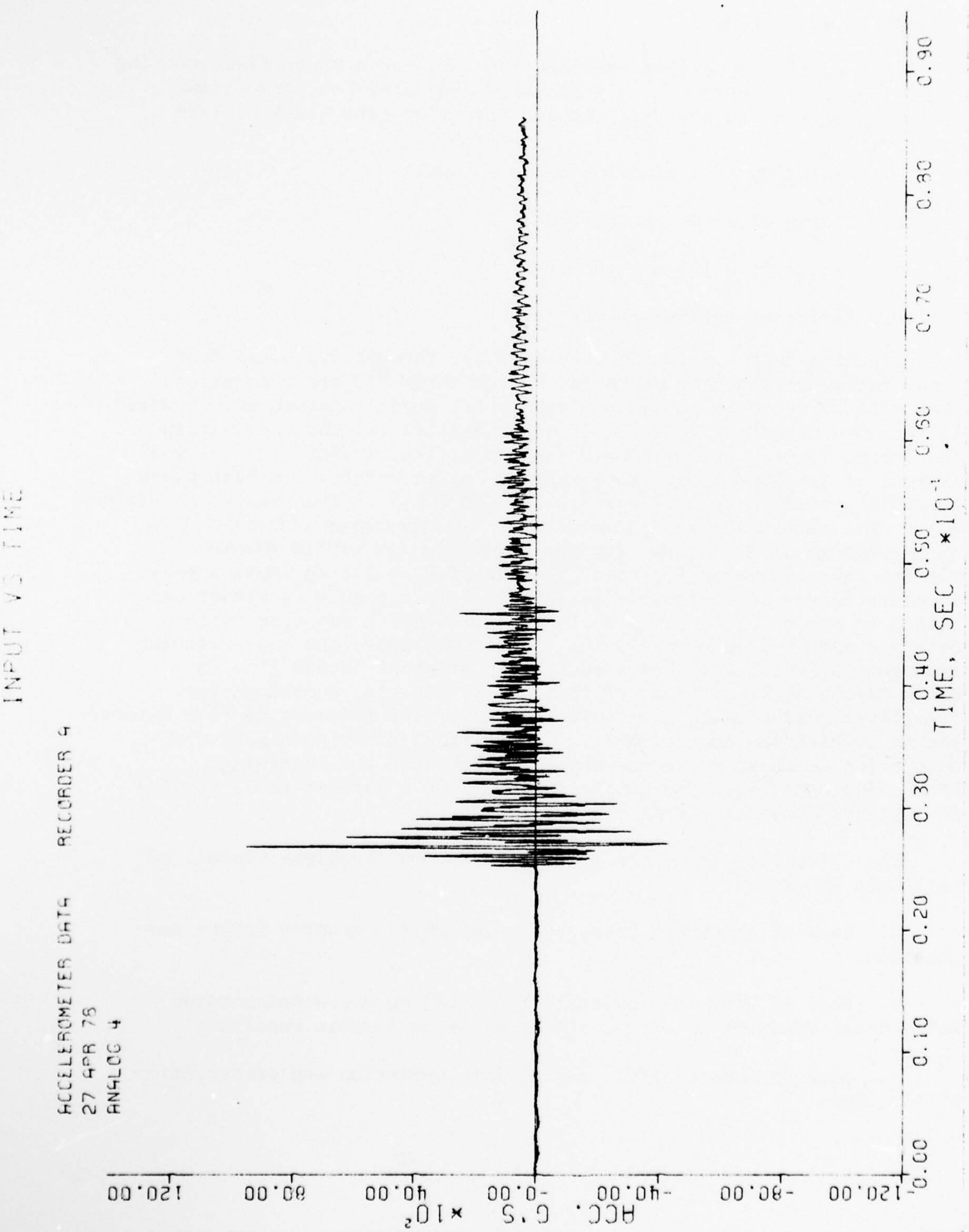


Figure 2.1-1. Acceleration versus time measured on floor of tank. Piezoelectric accelerometer, no filtering. Note DC shift.

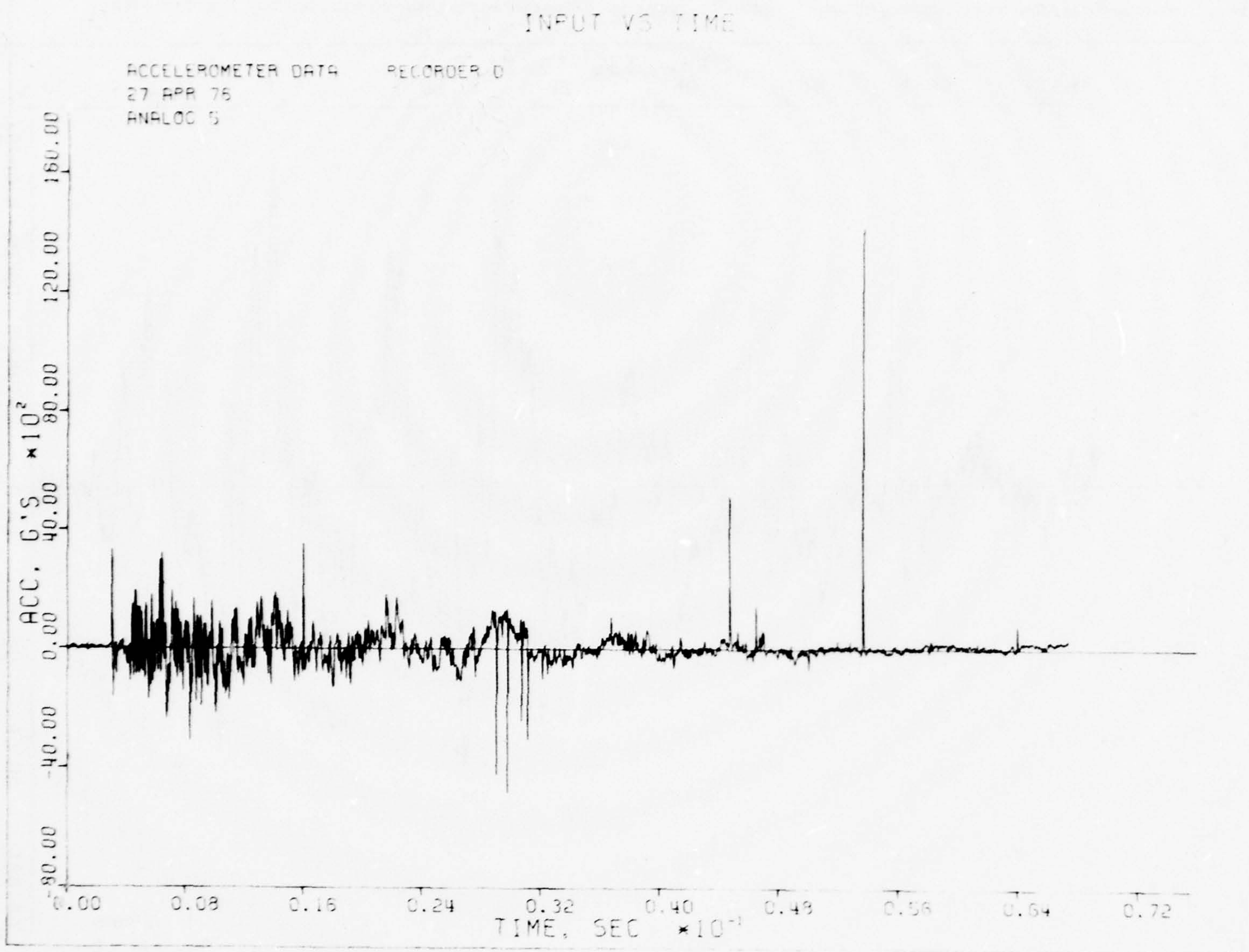


Figure 2.1-2. Acceleration versus time measured on floor of tank. Piezoresistive accelerometer, filtered at 10 kHz. (Several large spikes, apparently caused by tape-recorder dropout.)

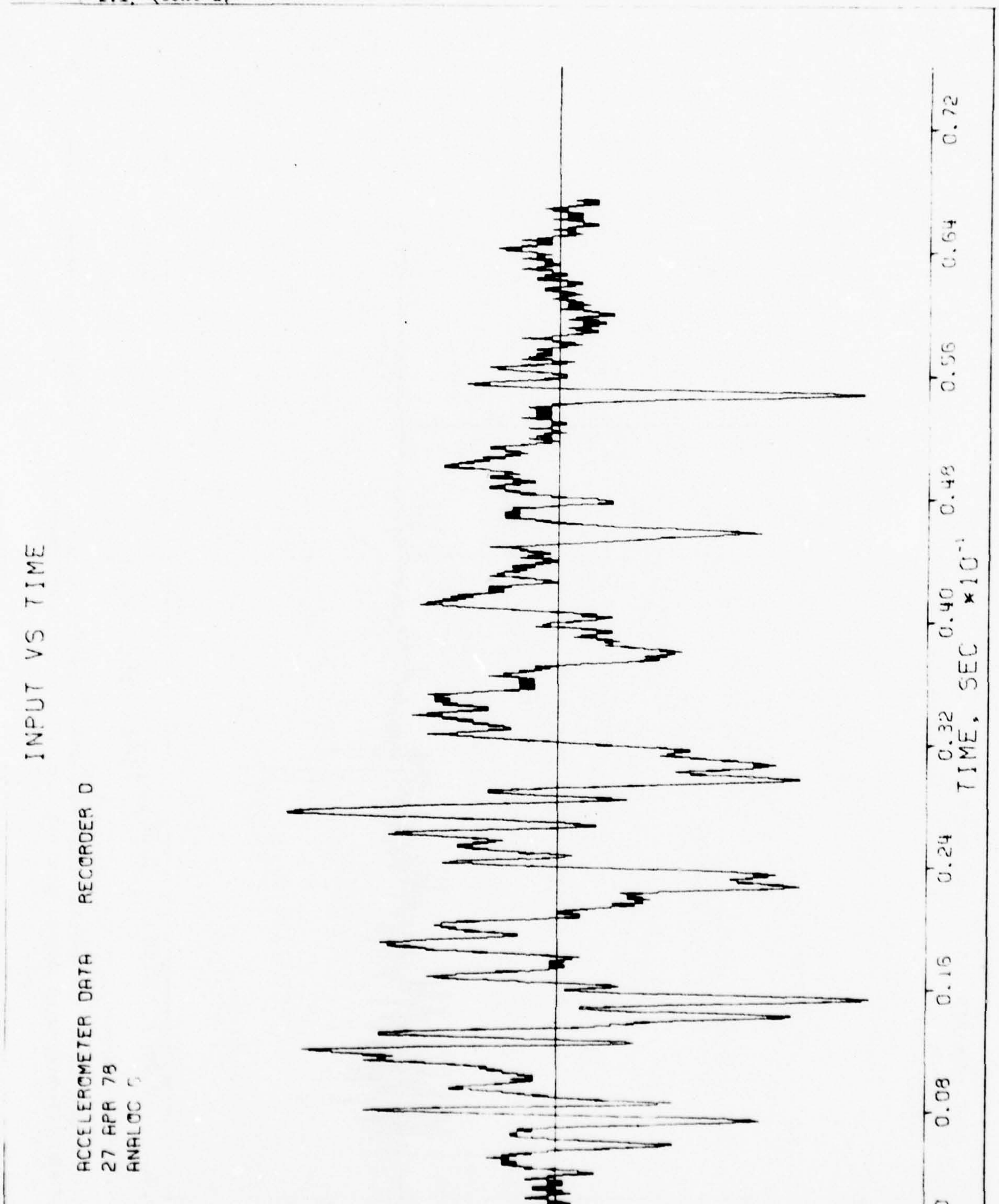


Figure 2.1-3. Acceleration versus time measured on floor of tank. Same piezoresistive accelerometer as shown in figure 2.1-2, but filtered at 1 kHz.

2.1 (Cont'd)

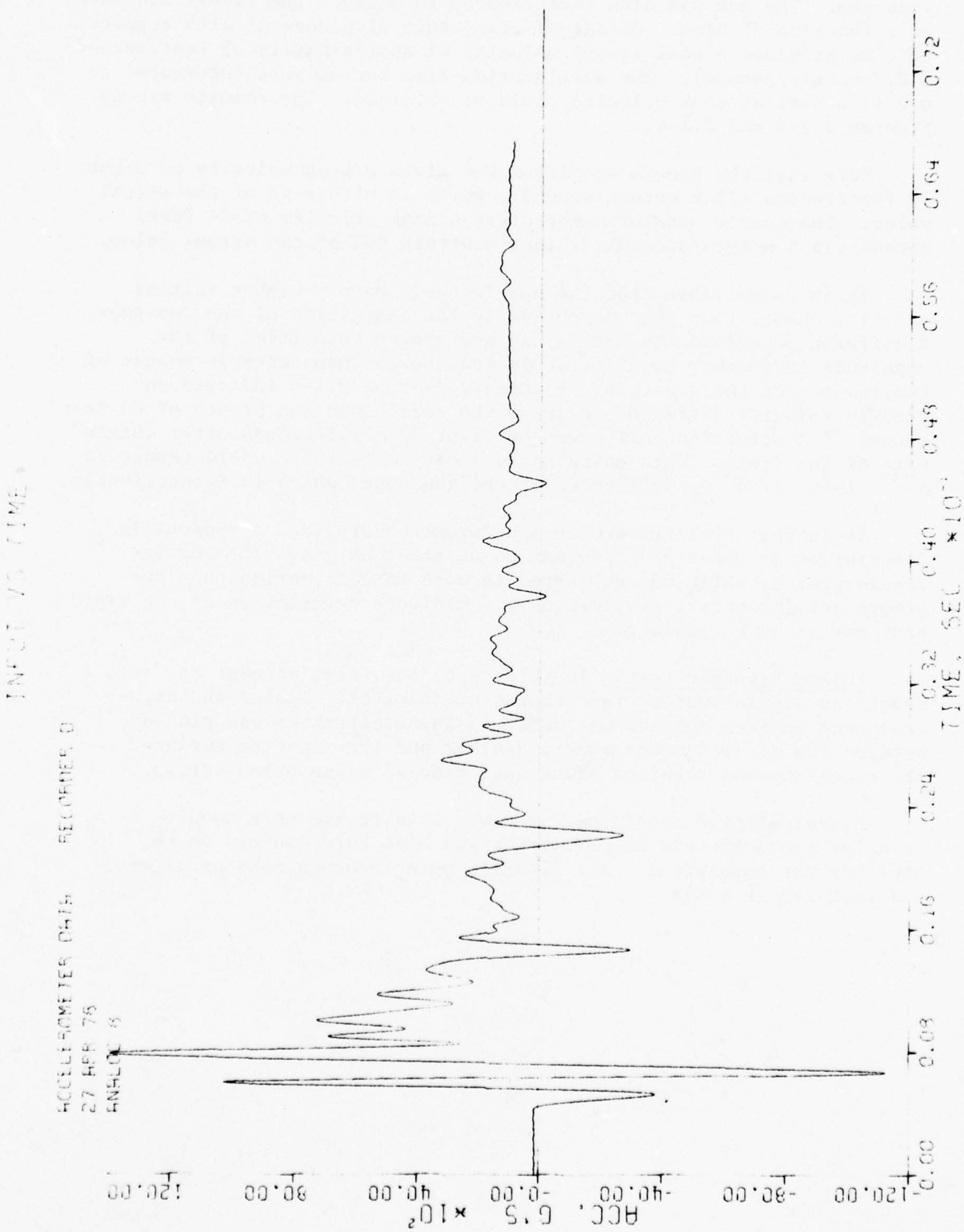


Figure 2.1-4. Acceleration versus time measured on floor of tank. Piezoelectric accelerometer, filtered at 1 kHz.

105-mm tank-gun test - in this test, piezoelectric accelerometers filtered at 4 kHz were mounted on the muzzle and breech of a 105-mm tank gun. The gun was also instrumented to measure the recoil distance as a function of time. Differentiating this displacement with respect to time provides a peak recoil velocity of approximately 35 feet/second (10.7 meters/second). The acceleration-time curves were integrated to see if a simiiar peak velocity could be obtained. The results are in figures 2.1-5 and 2.1-6.

Note that the breech accelerometer gives a peak velocity of about 38 feet/second (11.6 meters/second), which is within 9% of the actual value. The muzzle accelerometer gives a peak velocity of 51 feet/second (15.5 meters/second), which is within 46% of the actual value.

It is conceivable that the muzzle could have a higher initial velocity change than the breech due to the elasticity of the gun tube. A difference between the muzzle and the breech velocities of the magnitude indicated, however, would lead to an inconceivable amount of compression of the gun tube. Figures 2.1-5 and 2.1-6 indicate an average velocity difference between the muzzle and the breech of 20 feet/second (6.1 meters/second) over the first 30 milliseconds after muzzle exit of the round. This sustained velocity difference would result in a 6.8 inch (17.4 cm) deflection of the gun tube, which is inconceivable.

It is felt that the breech accelerometer provided a reasonable description of the rigid body motion of the tank gun. The muzzle accelerometer, which was subjected to more violent motion than the breech accelerometer, provided only a mediocre description of the rigid body motion of the tank gun.

105-mm howitzer test - in this test, the first attempt to "soft mount" an accelerometer (and thereby mechanically filter out high-frequency surface motion) was made. A layer of rubber was placed between the accelerometer mounting block and the mounting surface. The accelerometer mounting block was attached using nylon screws.

Piezoresistive accelerometers were used on the soft mount. A triaxial piezoelectric accelerometer was also hard mounted on the howitzer for comparison. All channels were recorded both unfiltered and filtered at 4 kHz.

2.1 (Cont'd)

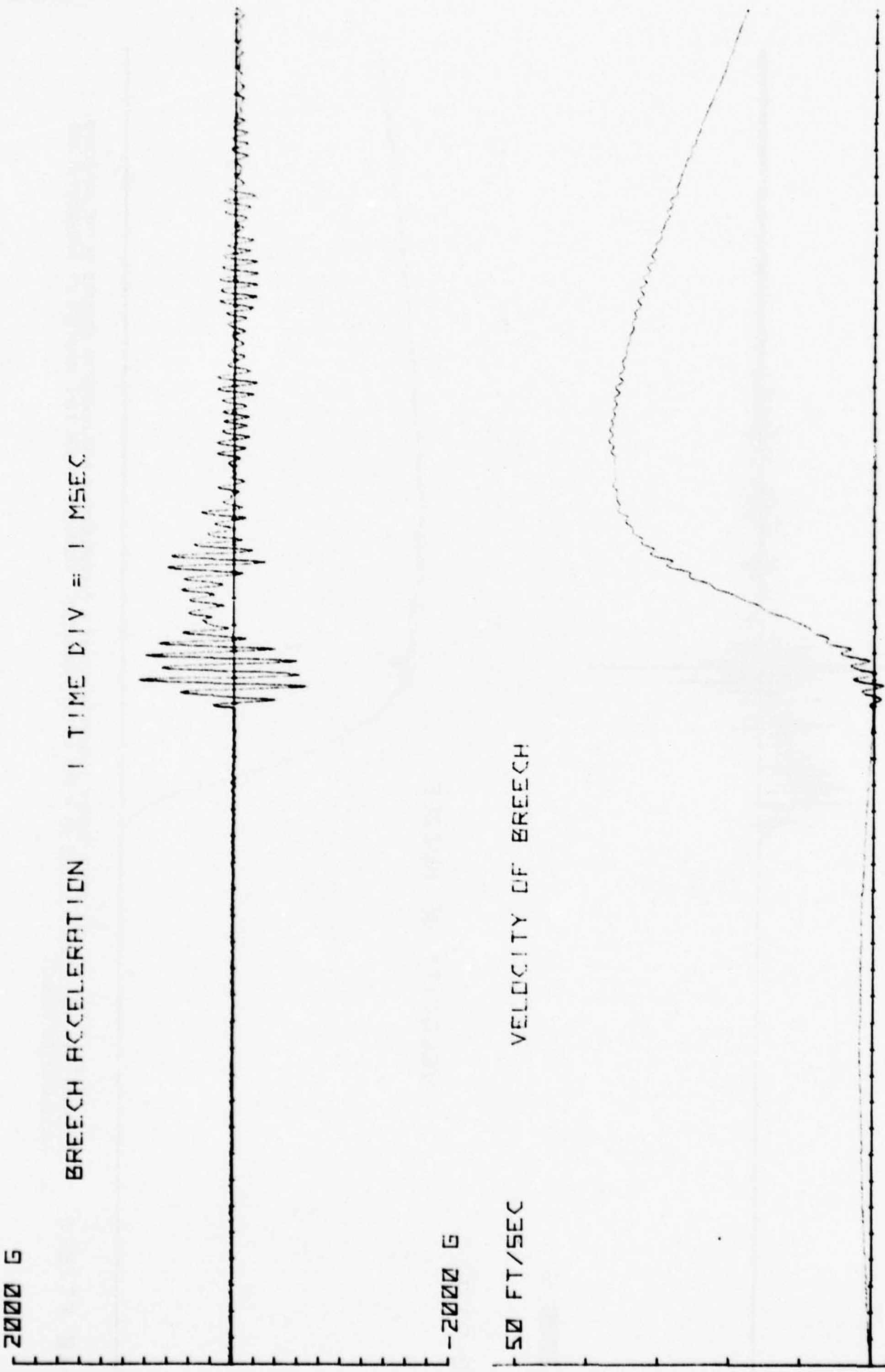


Figure 2.1-5. Acceleration versus time measured by a piezoelectric accelerometer mounted on the muzzle of a 105-mm tank gun. Data filtered at 4 kHz before recording. Velocity versus time obtained by integrating the accelerometer signal.

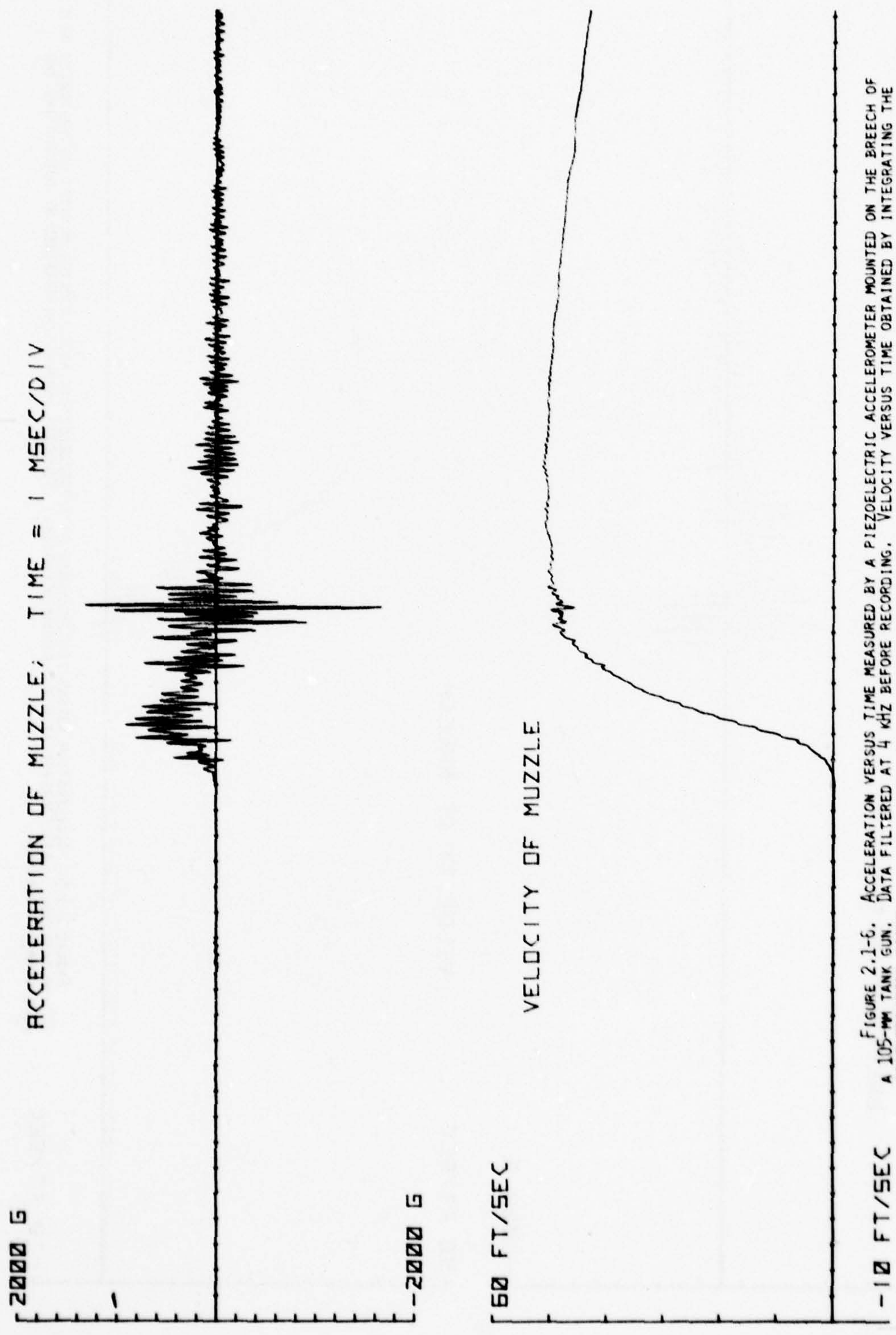


FIGURE 2.1-6. ACCELERATION VERSUS TIME MEASURED BY A PIEZOELECTRIC ACCELEROMETER MOUNTED ON THE BREECH OF A 105-MM TANK GUN. DATA FILTERED AT 4 KHZ BEFORE RECORDING. VELOCITY VERSUS TIME OBTAINED BY INTEGRATING THE ACCELEROMETER SIGNAL.

2.1 (Cont'd)

The signal from the soft-mounted accelerometer is shown in figure 2.1-7. Note that the soft mount oscillated at approximately ∿ 600 Hz. The mounting configuration used had little damping.

The unfiltered signal from the soft-mounted accelerometer was essentially the same as the signal filtered at 4 kHz. The unfiltered signal from the hard-mounted accelerometer was substantially different from the signal filtered at 4 kHz due to the accelerometer ringing at its own natural frequency.

Figure 2.1-8 compares the hard-mounted accelerometer with the soft-mounted accelerometer (both signals filtered at 4 kHz). The actual velocity change during recoil for this type of round should be approximately 35 feet/second (10.7 meters/second). Although a cleaner record was obtained with the hard-mounted accelerometer, DC shift (typical of piezoelectric accelerometers) caused a drift in the velocity plot.

<u>155-mm howitzer test</u> - in this test a piezoresistive accelerometer and a damped strain-gage accelerometer were mounted on the breech of a 155-mm howitzer. In addition, a damped strain-gage accelerometer was mounted on the forward end of the recoil mechanism (a recoiling part). All accelerometers were hard mounted to the weapon. All signals were low-pass filtered at 1 kHz before recording. No extra tape-recorder channels were available to record the unfiltered signals.

This weapon was also instrumented to measure recoil distance as a function of time. Differentiating this displacement with respect to time gives a peak recoil velocity of 45.09 feet/second (13.7 meters/second) for round 9. The acceleration measured by the two breech-mounted accelerometers is shown in figure 2.1-9.

The two accelerometers agree quite well; the piezoresistive accelerometer (AH09C) indicates a peak recoil velocity of 45.89 feet/second (14.0 meters/second), which is within 2% of the value, and the strain-gage accelerometer indicates a peak recoil velocity of 45.2 feet/second (13.8 meters/second), which is within 1% of the value.

Figure 2.1-10 compares the breech acceleration with the acceleration measured at the forward end of the recoil mechanism; these two measurements agree quite well until muzzle exit. The peak recoil velocity from the forward gage is 44.98 feet/second (13.7 meters/second), which is within 1% of the actual value.

These results are very good. The curves obtained agree quite well with other measurements of the weapon motion and with what one would expect for rigid body motion of the weapon. The error in shock measurements of 5% is typical; in this case, the error appears to be much less (1% or 2%).

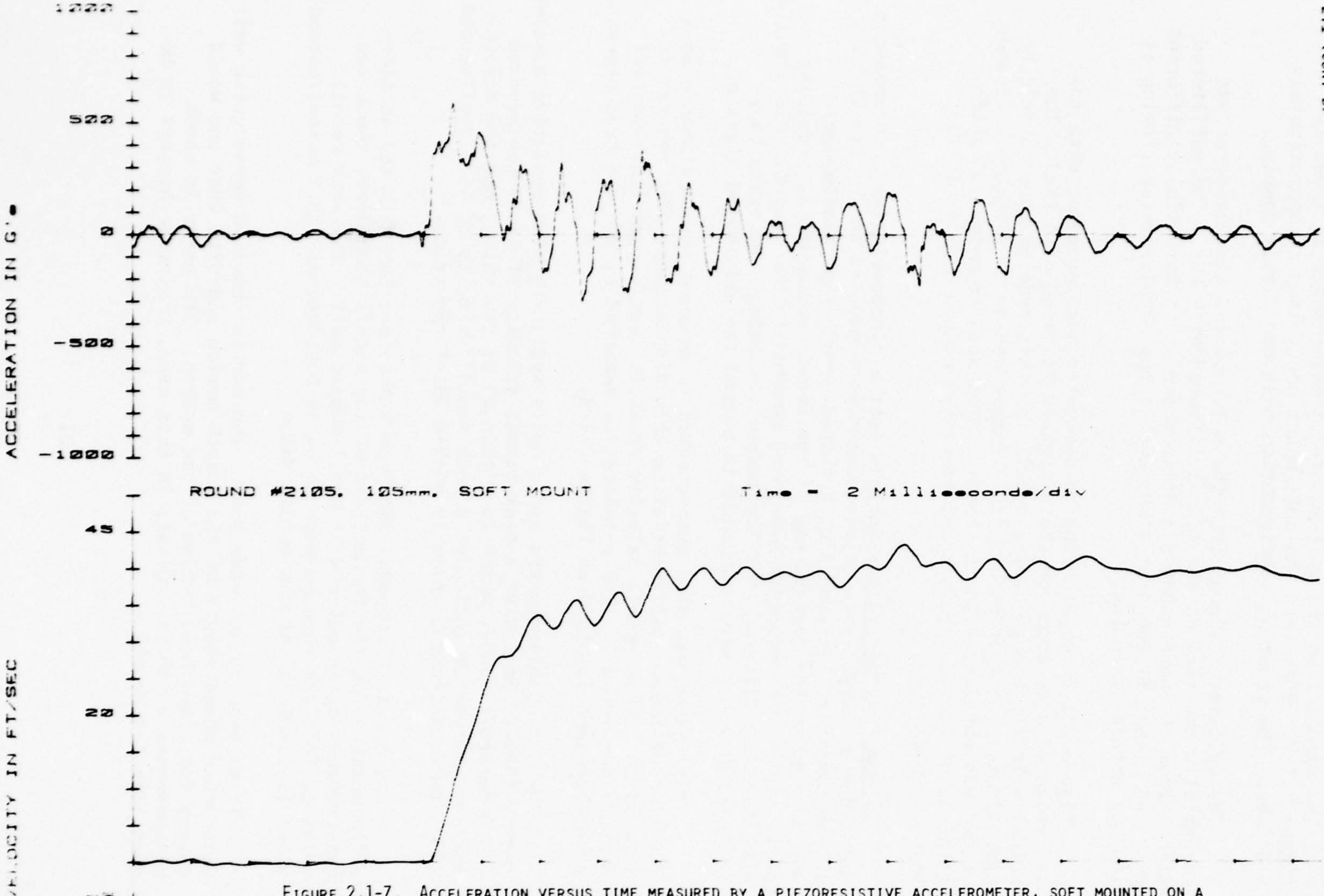


FIGURE 2.1-7. ACCELERATION VERSUS TIME MEASURED BY A PIEZORESISTIVE ACCELEROMETER, SOFT MOUNTED ON A 105-MM HOWITZER IN THE LINE OF FIRE. DATA WERE FILTERED AT 4 KHZ BEFORE RECORDING. NOTE THE 1-KHZ RING OF THE SOFT MOUNT.

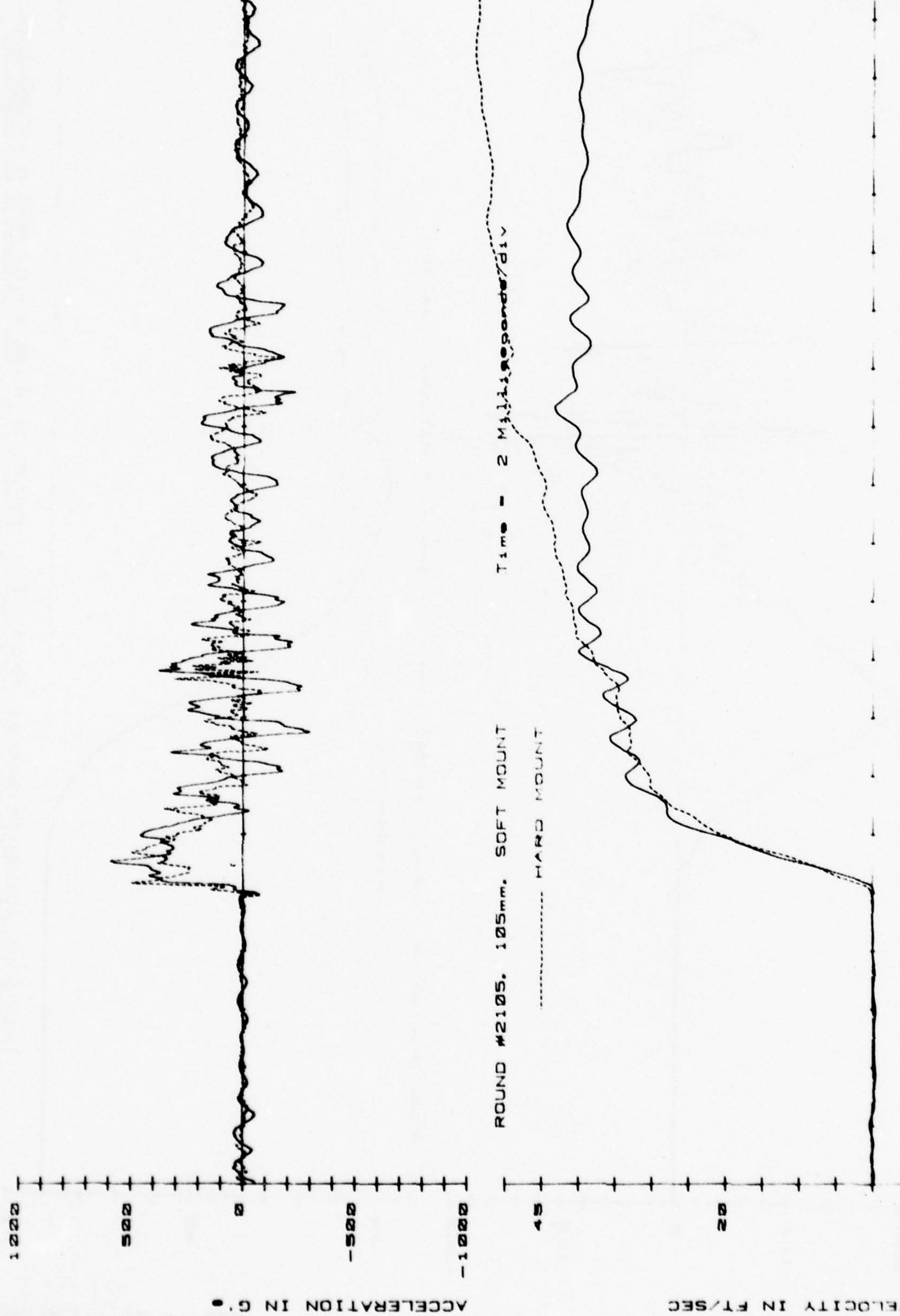


Figure 2.1-2. Comparison of acceleration measured by soft-mounted piezoresistive accelerometer and hard-mounted piezoelectric accelerometer on 105-mm howitzer. Data filtered at 4 KHz before recording.

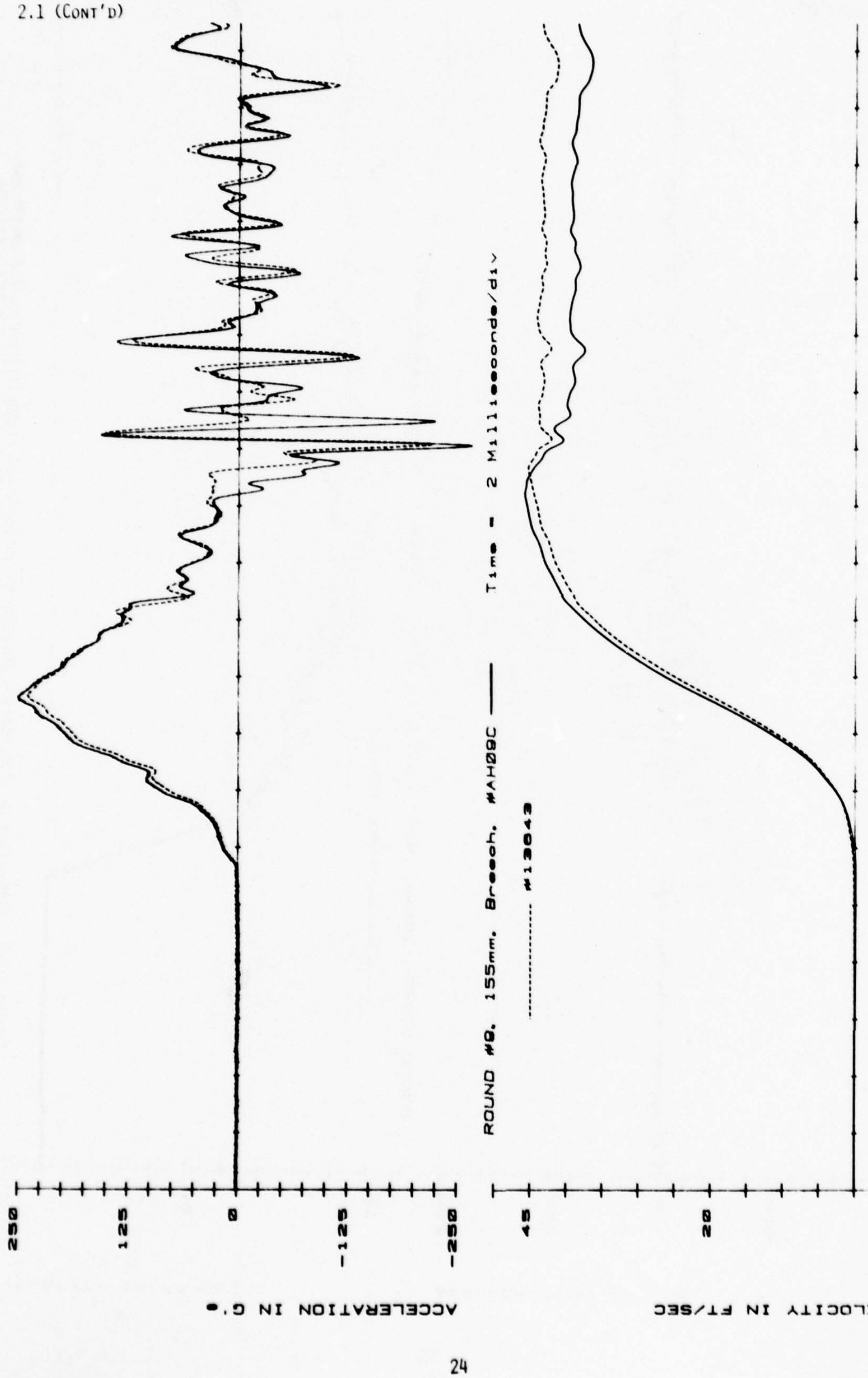


FIGURE 2.1-9. ACCELERATION MEASURED ON BREECH OF 155-MM HOWITZER, IN THE LINE OF FIRE. AH09C IS A PIEZORESISTIVE ACCELEROMETER; 13643 IS A STRAIN-GAGE ACCELEROMETER DAMPED AT 0.7 OF CRITICAL. BOTH ACCELEROMETERS HARD MOUNTED AND FILTERED ELECTRICALLY AT 1 KHZ BEFORE RECORDING.

2.1 (Cont'd)

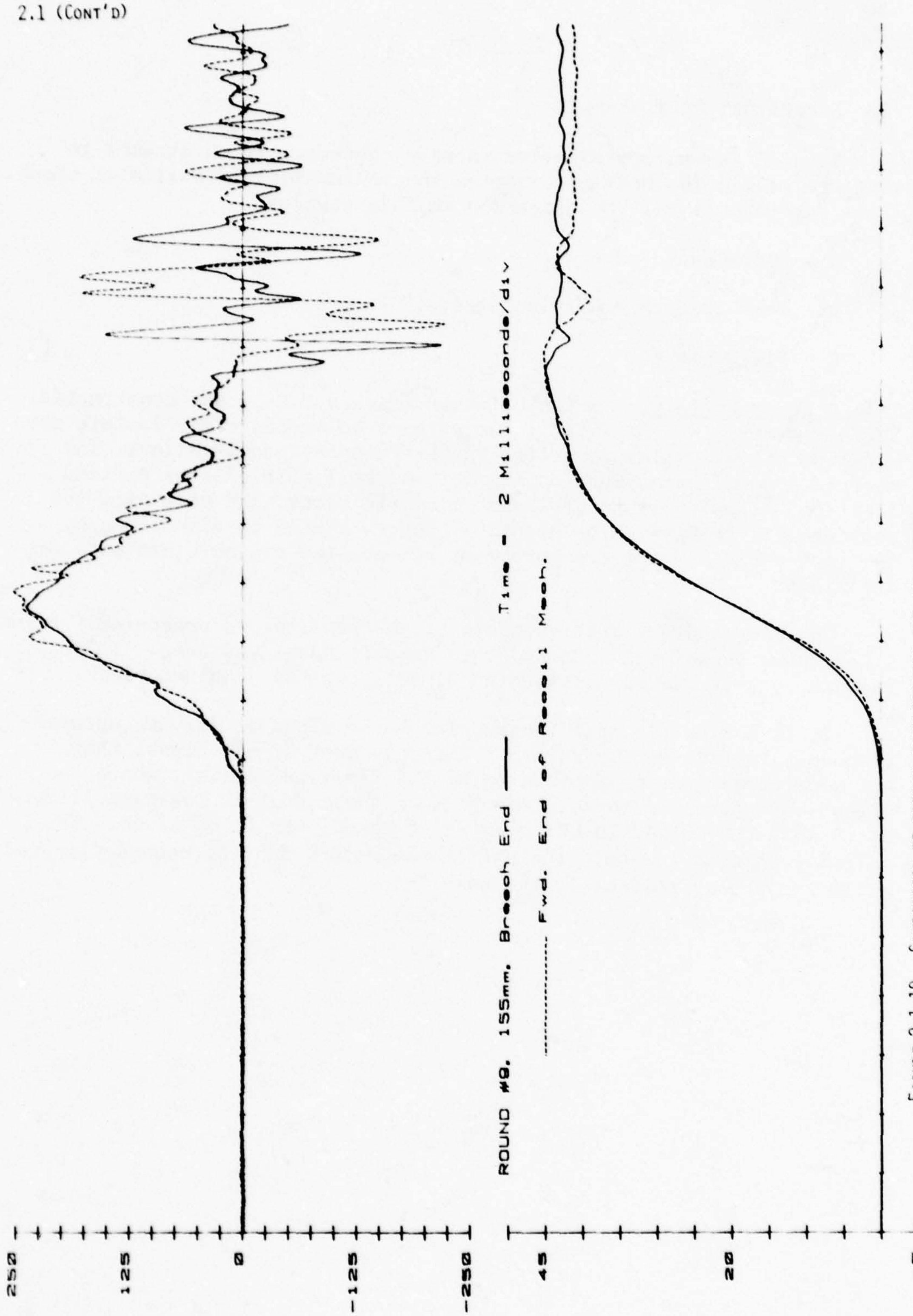


Figure 2.1-10. Comparison of breech acceleration and acceleration of forward end of recoil mechanism. Hard-mounted strain-gage accelerometers were used and signals were filtered at 1 KHz before recording.

2.2 LABORATORY TEST RESULTS

Several laboratory experiments were conducted in an attempt to simulate ballistic shock and improve the measurement of ballistic shock. Three experiments will be discussed in this section:

a. Soft-mount tests.

b. Back-to-back comparison tests.

c. Plate tests.

Soft-mount tests - a test fixture (figure 2.2-1) was constructed. Various materials were tried in an attempt to mechanically isolate the piezoresistive accelerometer from high-frequency acceleration. The materials were tested by dropping a steel ball bearing from a fixed position, allowing it to strike an aluminum block, and examining the accelerometer output. The mounting block was held on five sides by the test material; the accelerometer was mounted on the sixth side of the block.

Uncalibrated qualitative plots of the results are presented. Figure 2.2-2 shows the signal obtained when no soft mount was used. In this case the accelerometer was mounted directly to the aluminum block.

It is noticeable that the accelerometer rings at its own natural frequency for the entire record. The only part of the signal that is not accelerometer ring appears to be the first two cycles, where the signal does not pass through zero. When the signal is low-pass filtered at 10 kHz, the damped 10-kHz ringing of the filter is obtained. The velocity changes for both the unfiltered record and the record filtered at 10 kHz are approximately the same.

2.2 (Cont'd)

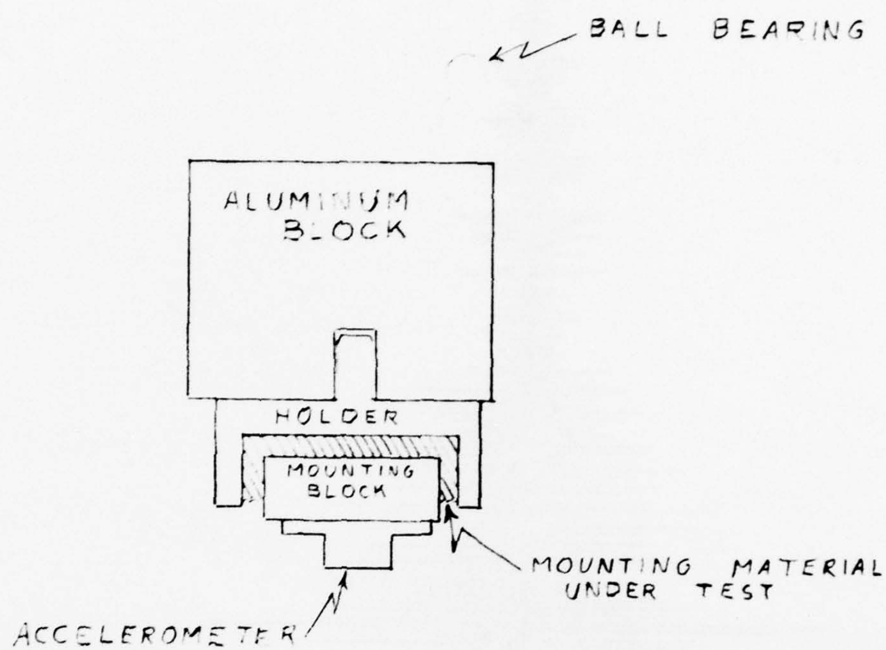


Figure 2.2-1. Test fixture used in soft-mount experiments.

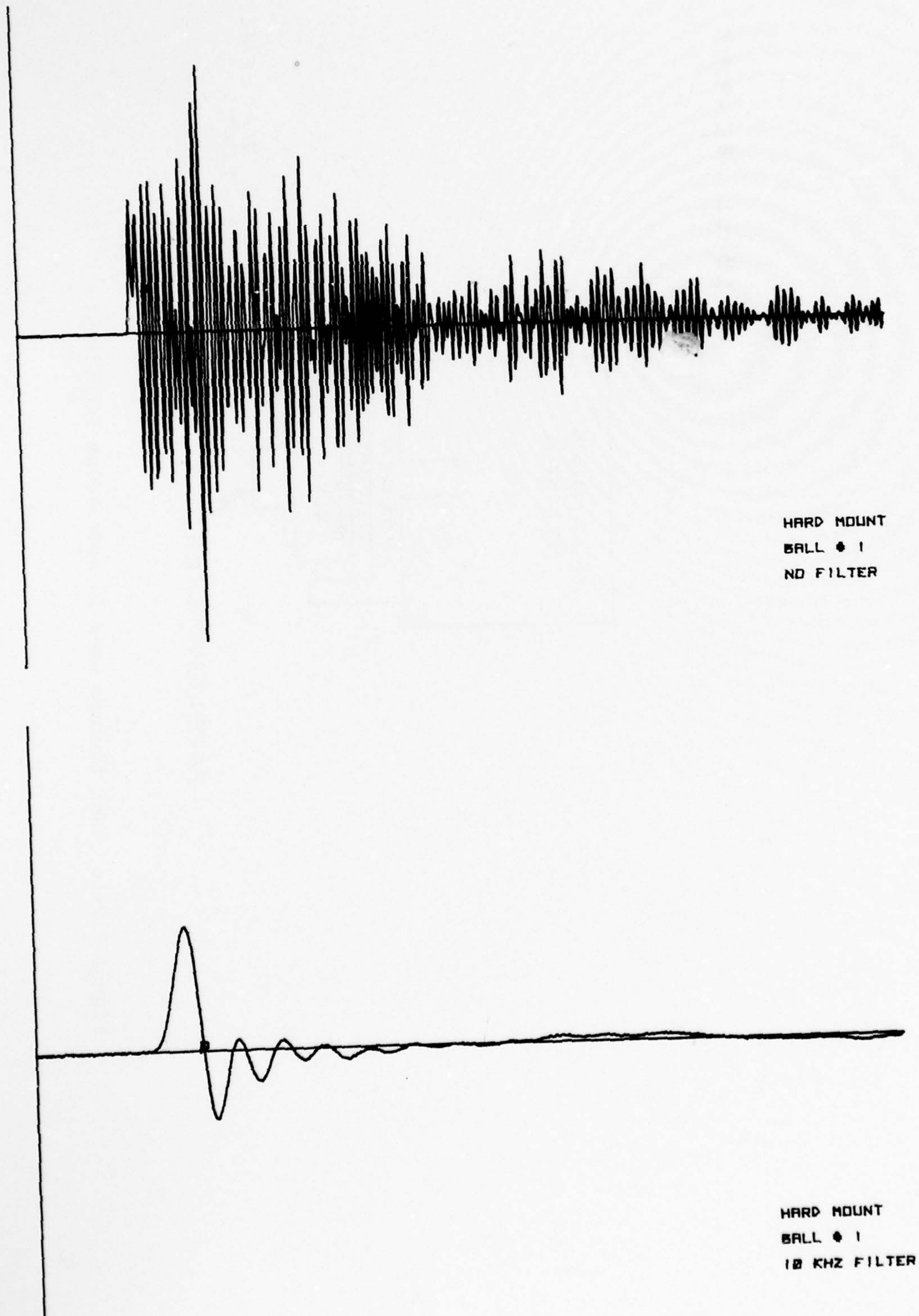


Figure 2.2-2. Acceleration versus time using hard-mounted accelerometer.

2.2 (Cont'd)

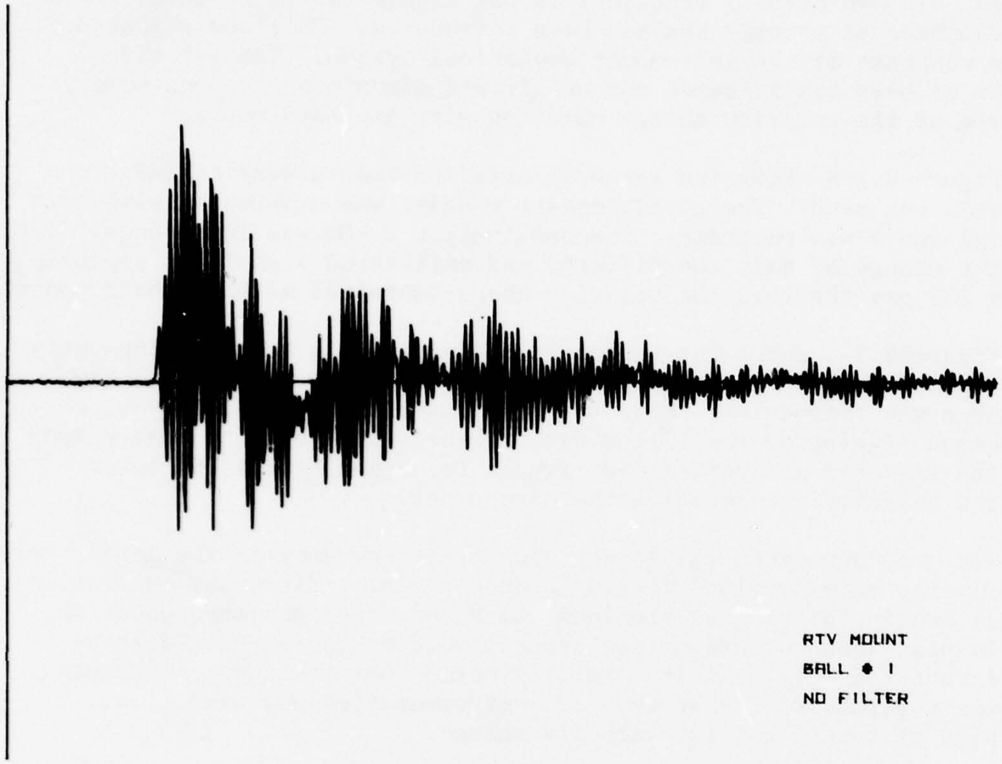
Figure 2.2-3 shows the results obtained when room-temperature-vulcanized (RTV) silicone rubber was used. The ringing of the accelerometer at its own natural frequency is not significantly reduced, but a new resonance at about 2 kHz has been introduced. This new resonance is the response of the soft-mount mechanical system. The velocity changes of both the filtered and unfiltered signals are approximately the same as the velocity change obtained with the hard mount.

Figure 2.2-4 shows the response obtained when a waxlike substance (Py-Seal) was used. The accelerometer ringing was suppressed with this material and a new resonance of approximately 2 kHz was introduced. The velocity change of both the filtered and unfiltered signals is approximately 15% greater than the velocity change obtained with the hard mount.

Figure 2.2-5 shows the response obtained when a nonhardening putty (Duxseal) was used. Accelerometer ringing was suppressed and no new resonance was introduced. When the signal was filtered at 10 kHz, only the damped ringing of the filter was present. The velocity change from both the filtered and unfiltered signals is approximately 15% lower than the velocity change using the hard mount.

The good agreement ($\pm 15\%$) of velocity change despite the large variation in the acceleration signals is encouraging. Since the excitation (a ball bearing hitting an aluminum block) was the same throughout the experiments, some measure of the shock should be the same. In these experiments the only quantity that indicated that the shock level was the same regardless of what type of instrumentation was used (i.e., what kind of mount) was the velocity change.

2.2 (CONT'D)



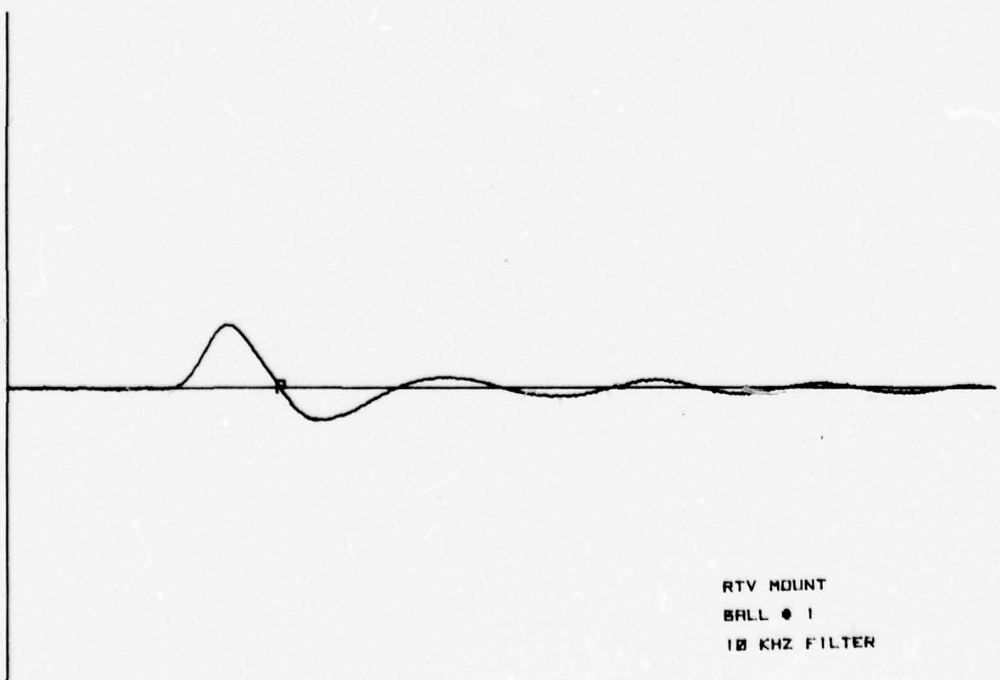


Figure 2.2-3. Acceleration versus time for the RTV soft mount.

2.2 (CONT'D)

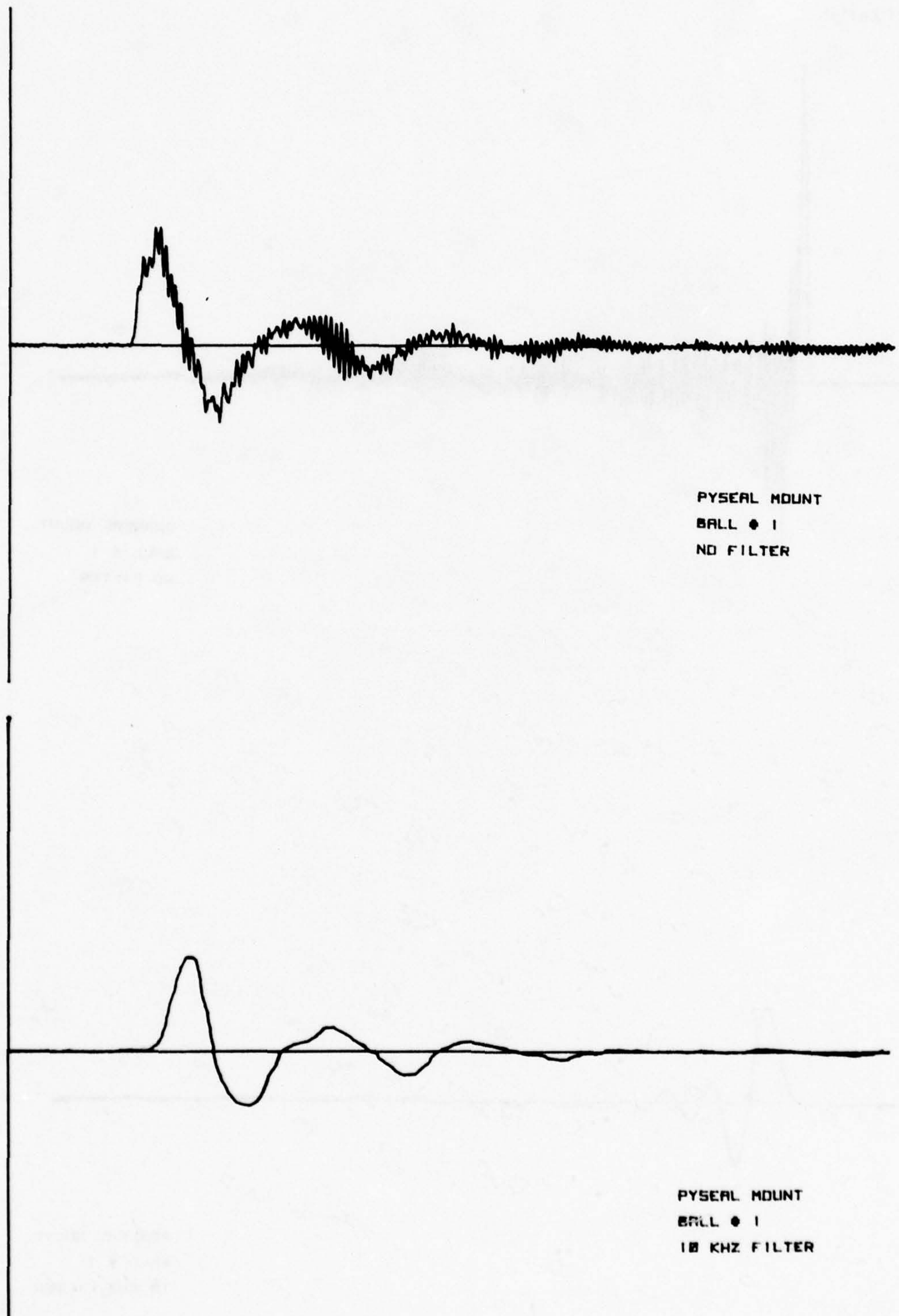
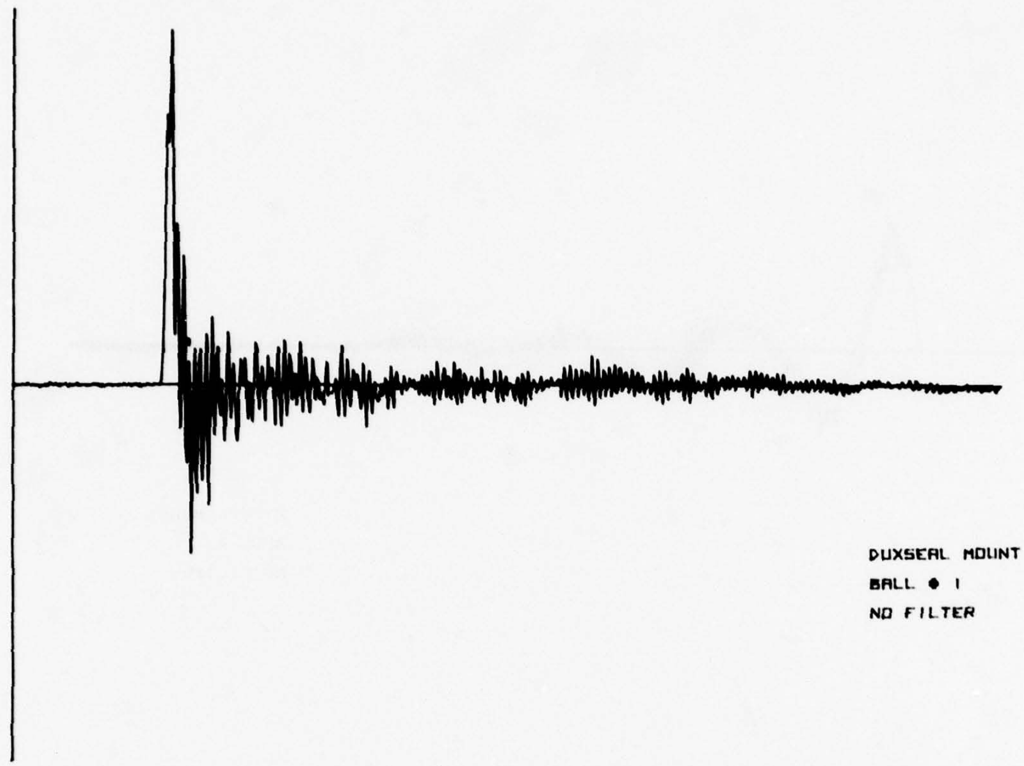


Figure 2.2-4. Acceleration versus time for the Py-Seal soft mount.

2.2 (CONT'D)



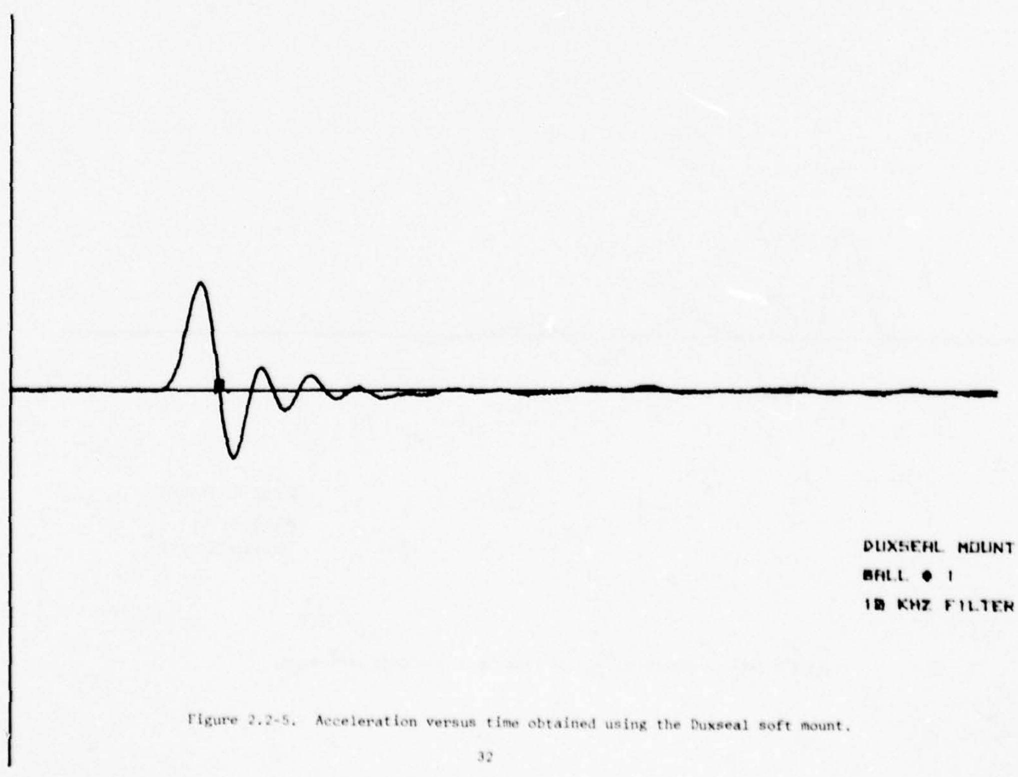


Figure 2.2-5. Acceleration versus time obtained using the Duxseal soft mount.

2.2 (Cont'd)

Recently, commercial mechanical filters, similar to those used in this report, have been introduced. These filters use a butyl rubber material and advertise a resonance amplitude of only 3 dB, which implies quite high damping (0.5 of critical). Some of these filters have been ordered and will be tested in the near future.

Back-to-back comparison tests - a piezoresistive and a piezoelectric accelerometer were mounted back-to-back on an aluminum cube. This cube was then attached to a protective structure, which was hit with a sledge hammer and had a ball bearing dropped on it.

Figure 2.2-6 shows the unfiltered response of the two accelerometers to a ball-bearing drop. Because of the complicated path between the surface struck by the ball bearing and the accelerometers, little ringing at the accelerometer natural frequency is present. The two signals agree quite well except that three oscillations of the piezoelectric accelerometer near the end of the record are almost twice the amplitude of the piezoresistive signal. The frequency of these three large oscillations is lower than the accelerometer natural frequency.

Figure 2.2-7 shows the response to a sledge hammer on a longer time scale, filtered at 10 kHz. The signals agree quite well until the piezoelectric accelerometer experiences a DC shift.

Plate tests - steel accelerometer mounting blocks were welded to a piece of steel armorplate 1/4 inch (0.64 cm) thick as shown in figure 2.2-8. A ball bearing was dropped from a fixed height to strike an impact point in the center of the plate, approximately equidistant to all accelerometers.

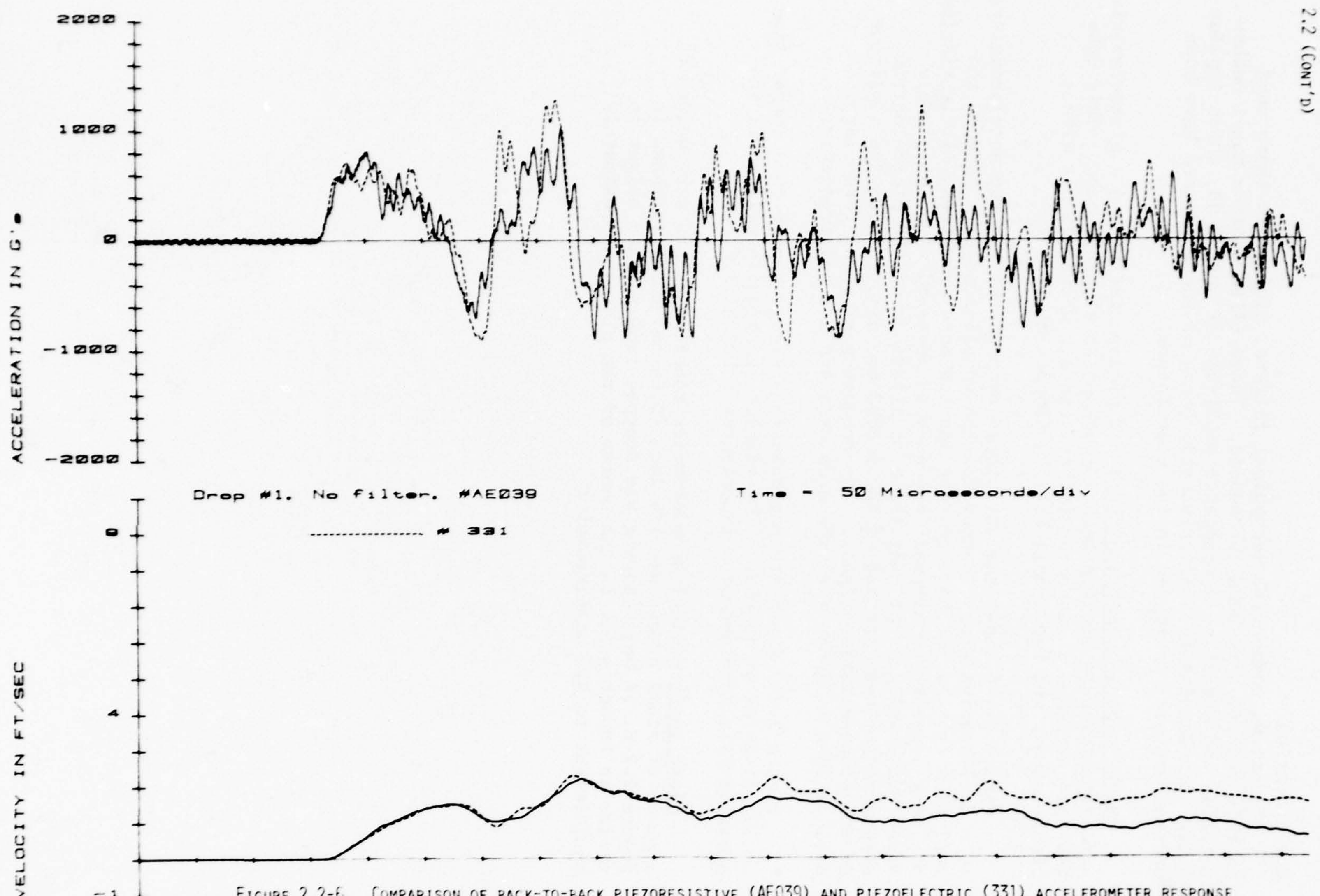


Figure 2.2-6. Comparison of back-to-back piezoresistive (AE039) and piezoelectric (331) accelerometer response to a ball-bearing drop, unfiltered. Note three large oscillations of piezoelectric accelerometer beginning at ~ 650 microseconds.

2.2 (CONT'D)

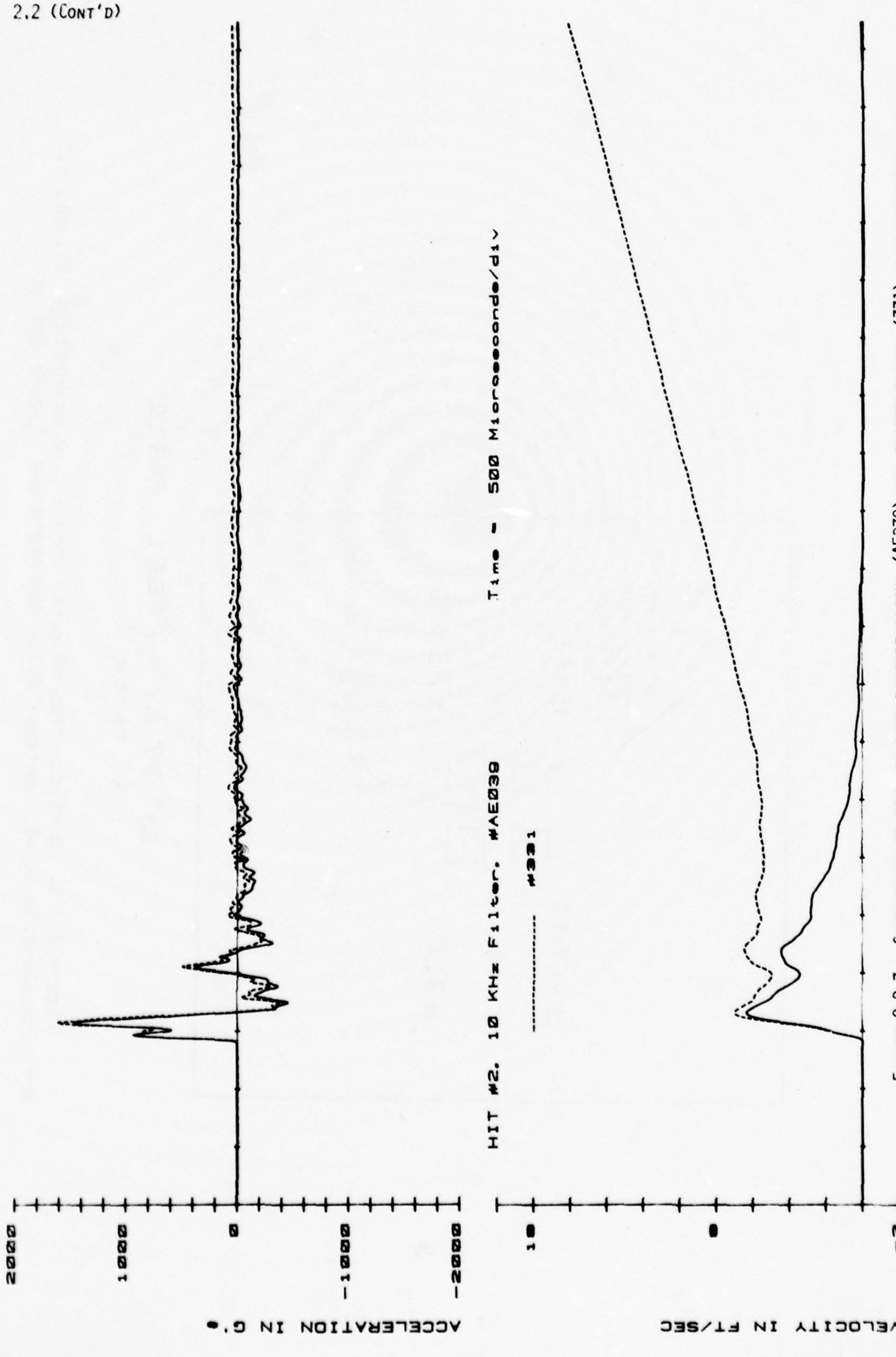


FIGURE 2.2-7. COMPARISON OF BACK-TO-BACK PIEZORESISTIVE (AE039) AND PIEZOELECTRIC (331) ACCELEROMETER RESPONSE TO A SLEDGE-HAMMER HIT. NOTE THE EFFECT OF THE DC SHIFT PRESENT IN THE PIEZOELECTRIC ACCELEROMETER SIGNAL.

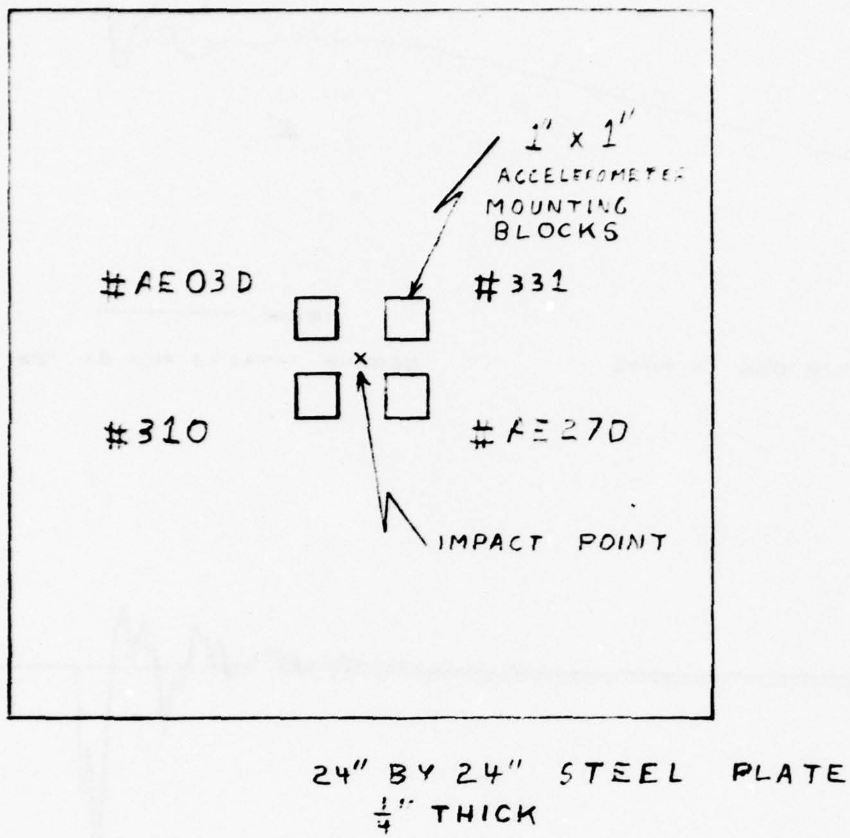


Figure 2.2-8. Configuration of accelerometers on armorplate; 331 and 310 are piezoelectric accelerometers; AE03D and AE27D are piezoresistive.

2.2 (Cont'd)

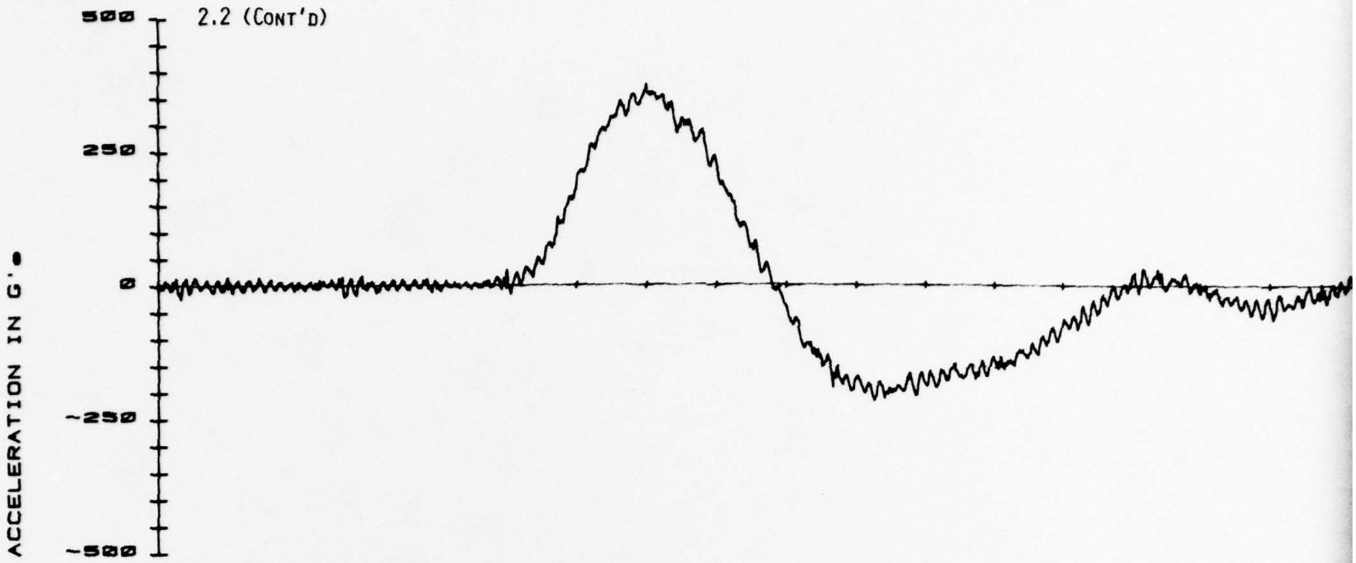
Figure 2.2-9 shows the response of all four accelerometers to drop 8. In this drop, several layers of tape were placed over the impact point. This modification allowed a smooth, long-time-duration ($\sim$ 200-microseconds) application of the shock. For this kind of shock, all accelerometers respond in a similar manner.

Figure 2.2-10 shows the response of the accelerometers to a ball-bearing impact on the bare plate. All four accelerometers indicate that the ball bearing was in contact with the plate for approximately 30 microseconds. The piezoelectric accelerometers produce the largest peak accelerations (7700 g's from 331 and -2800 g's from 310). The piezoresistive accelerometers produce significantly lower peak accelerations (1000 g's from AE03D and 930 g's from AE27D).

Because of the configuration of the accelerometers, it is impossible for the ball bearing to have hit closer to both the piezoelectric accelerometers; it is therefore not likely that the actural acceleration level was higher on both piezoelectric accelerometers than it was on either of the piezoresistive accelerometers.

The peak accelerations indicated by the piezoelectric accelerometers occur well after the actual impact of the ball bearing. In the case of accelerometer 331, the peak acceleration is almost twice the amplitude of the acceleration obtained while the ball bearing was in contact with the plate.

2.2 (Cont'd)



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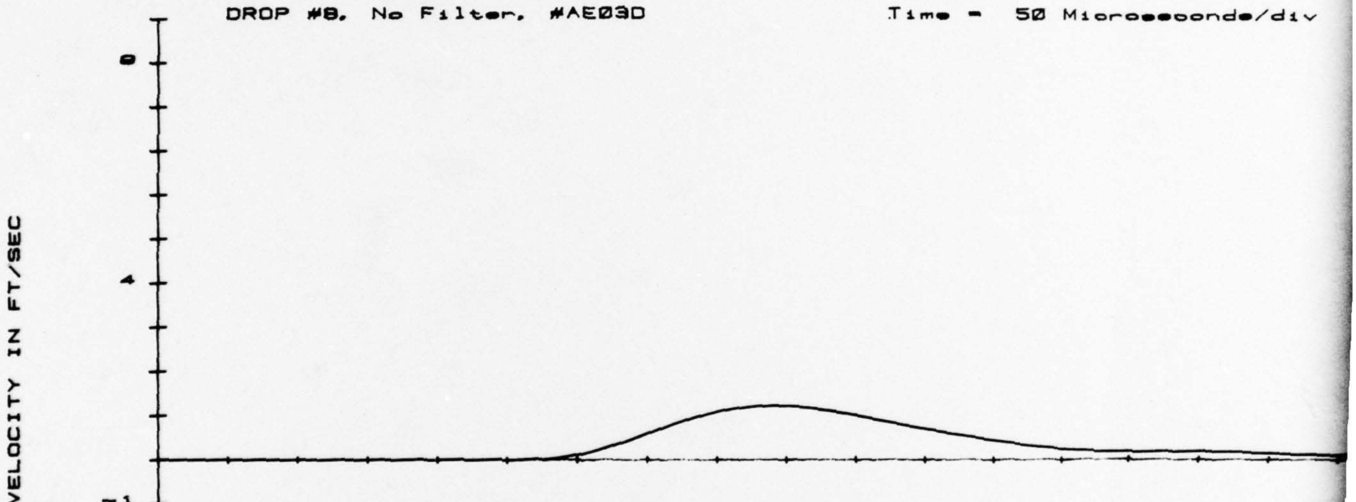

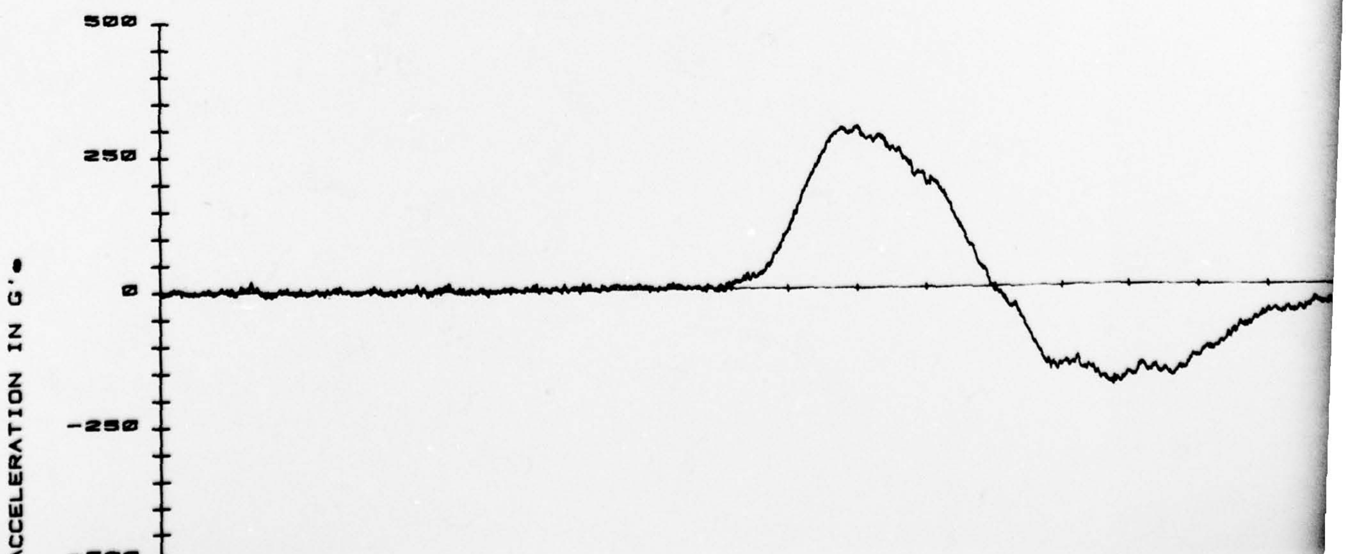

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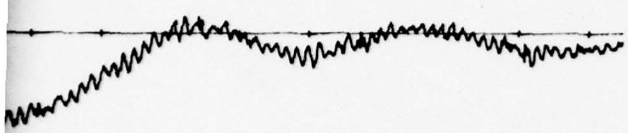

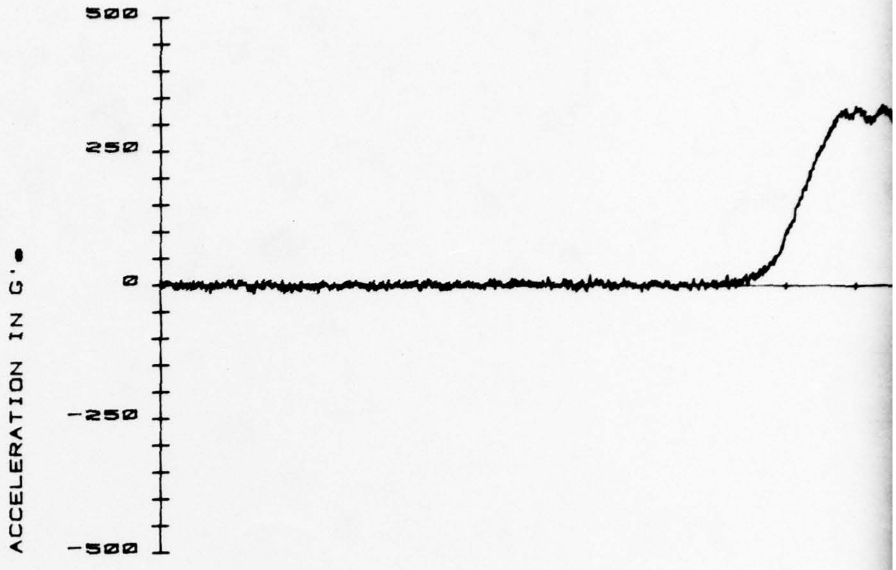

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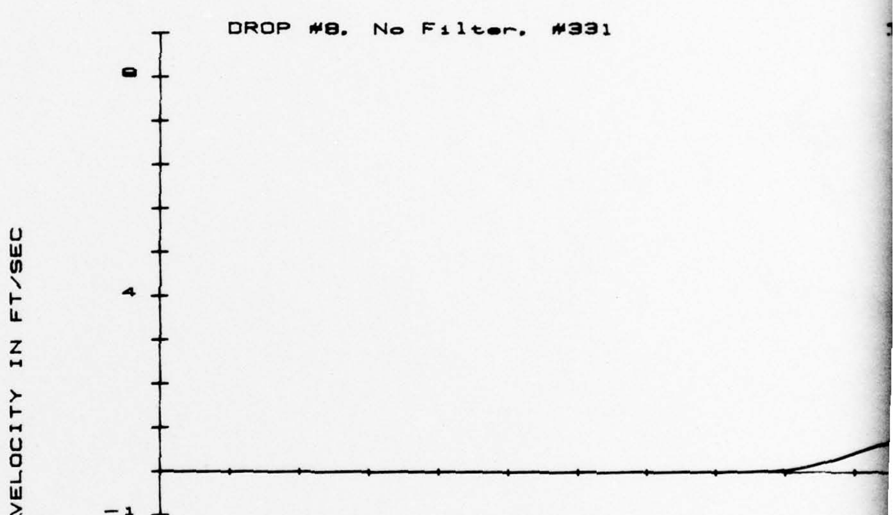

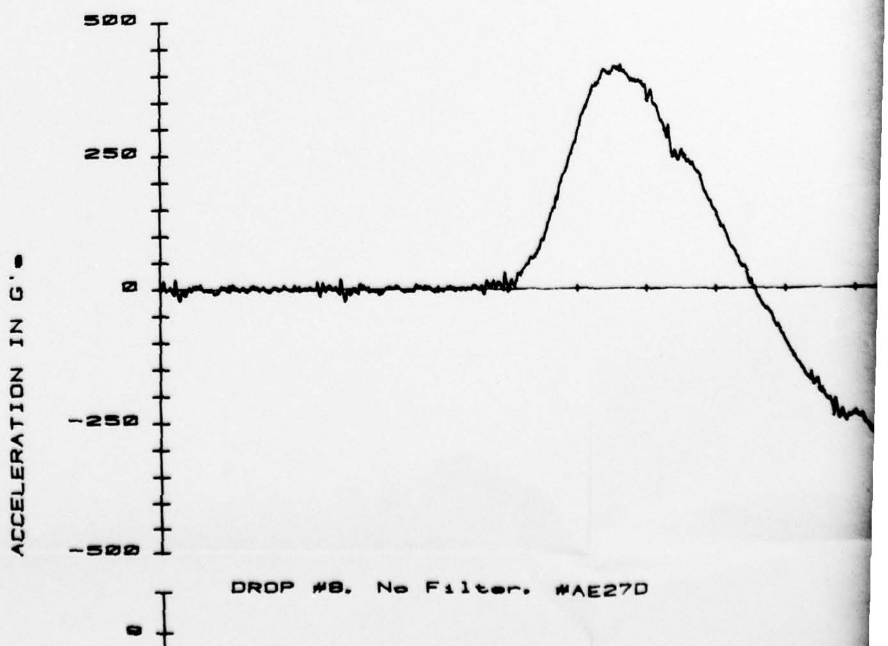

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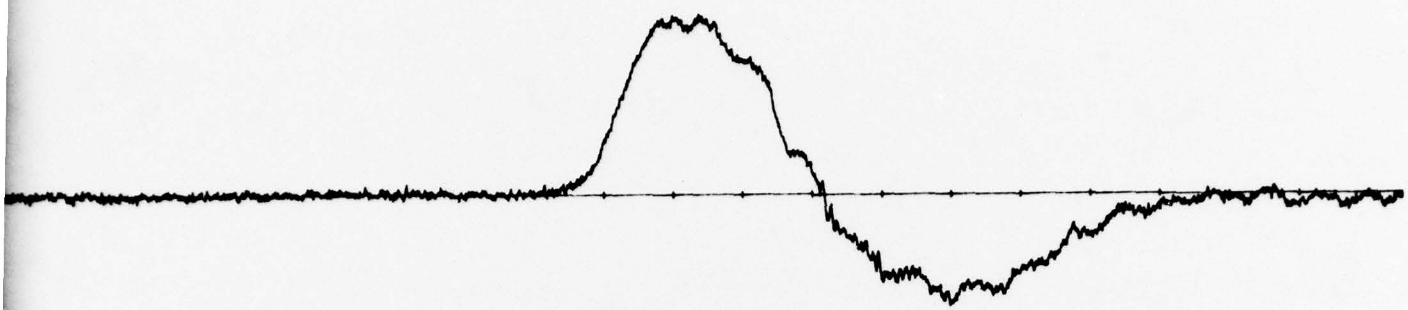

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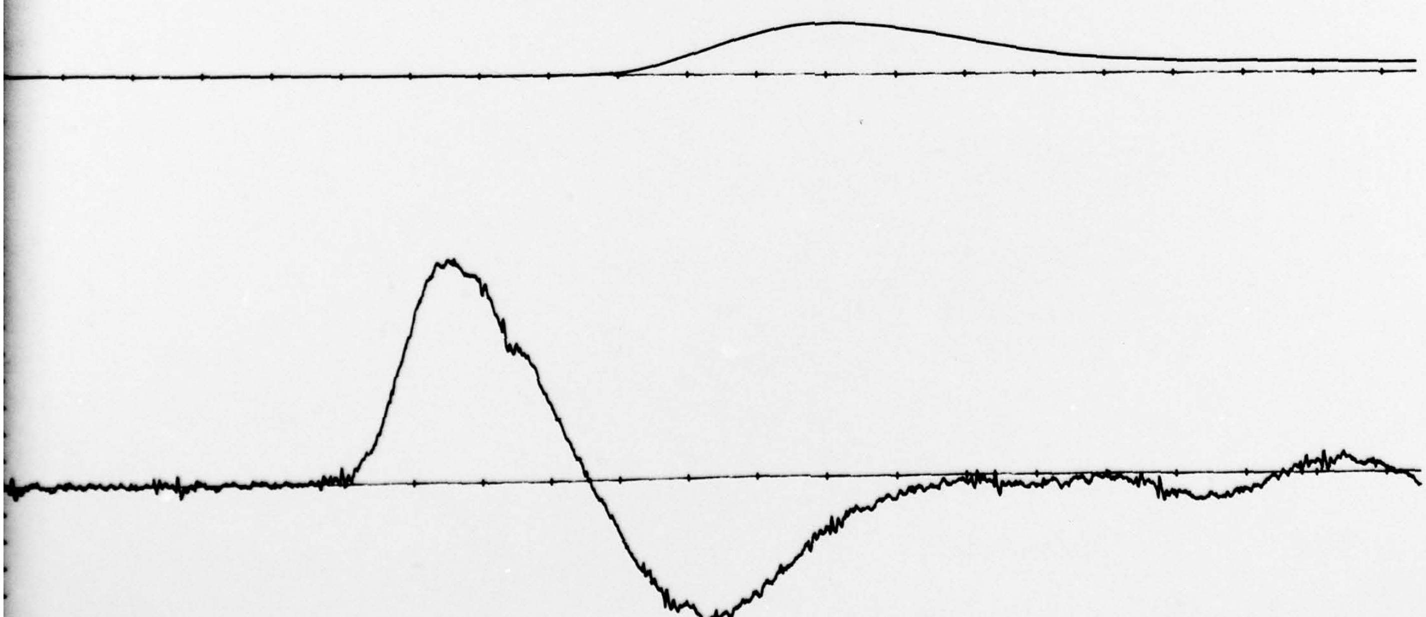

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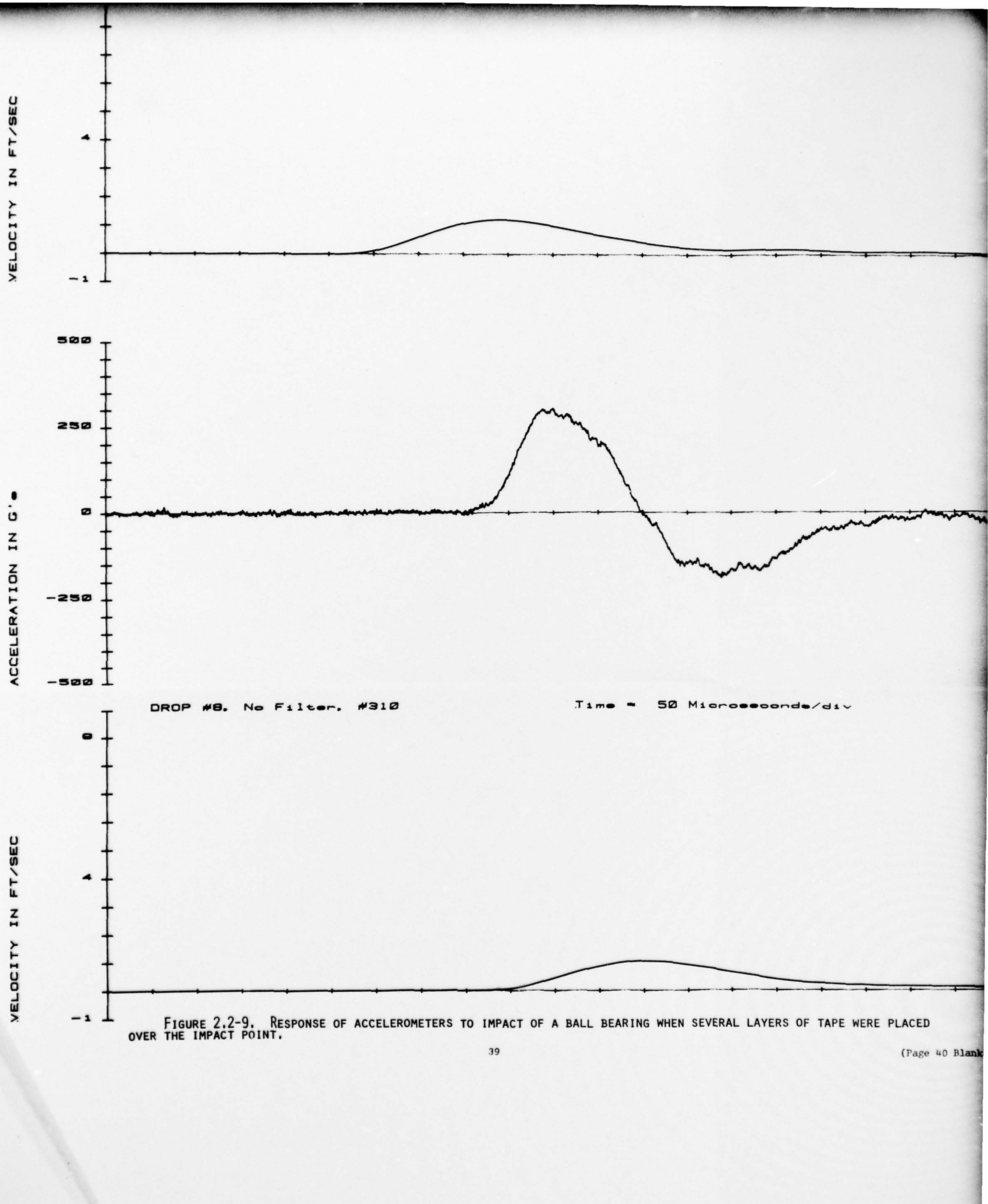
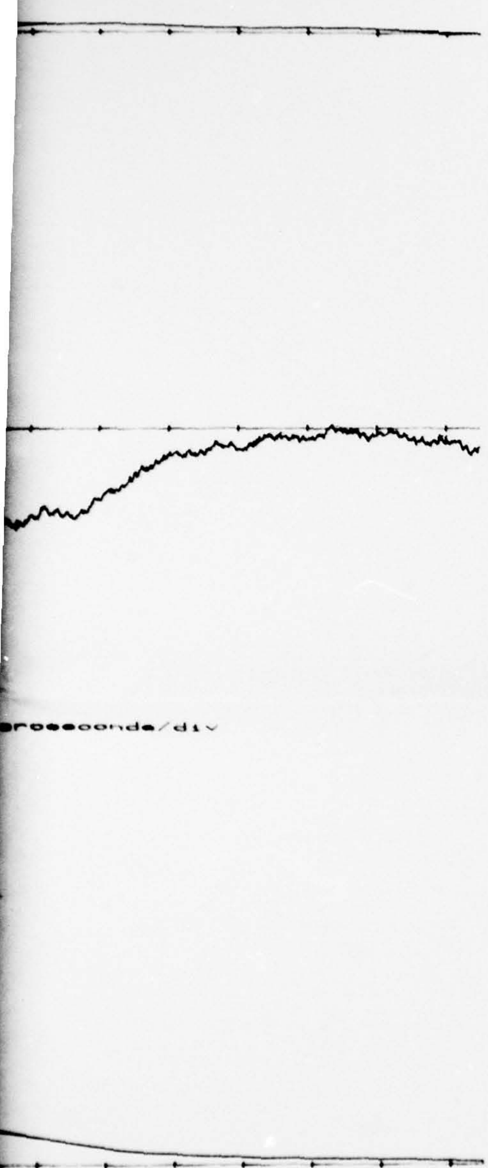
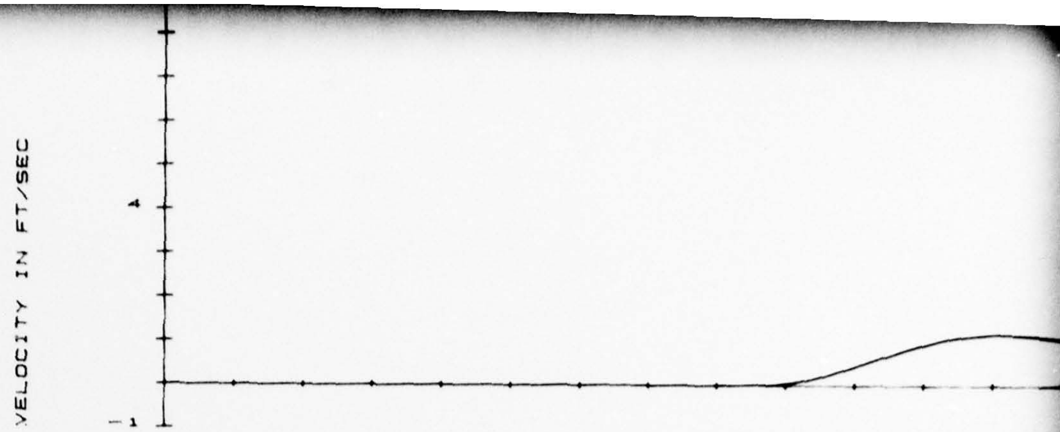
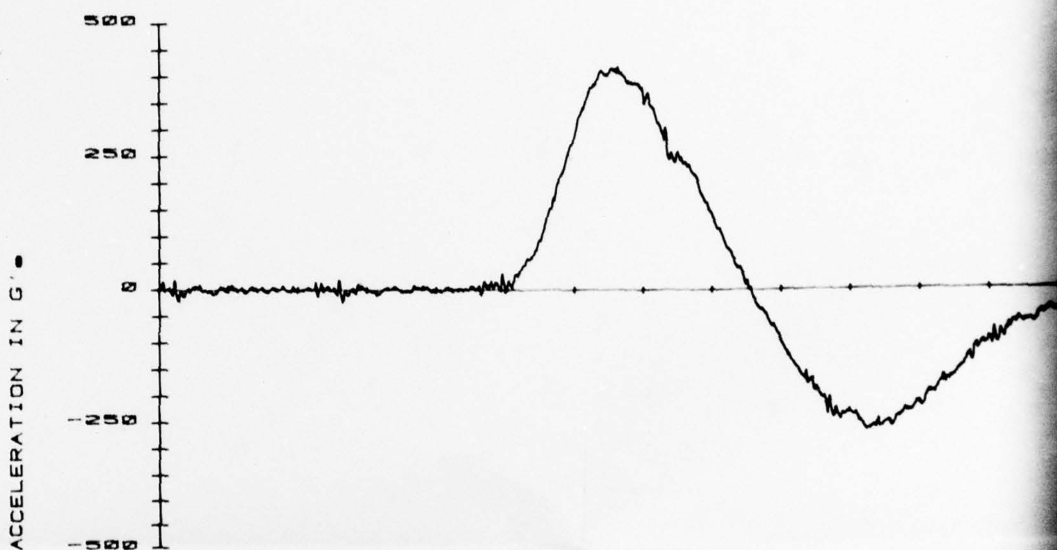


FIGURE 2.2-9. RESPONSE OF ACCELEROMETERS TO IMPACT OF A BALL BEARING WHEN SEVERAL LAYERS OF TAPE WERE PLACED OVER THE IMPACT POINT.







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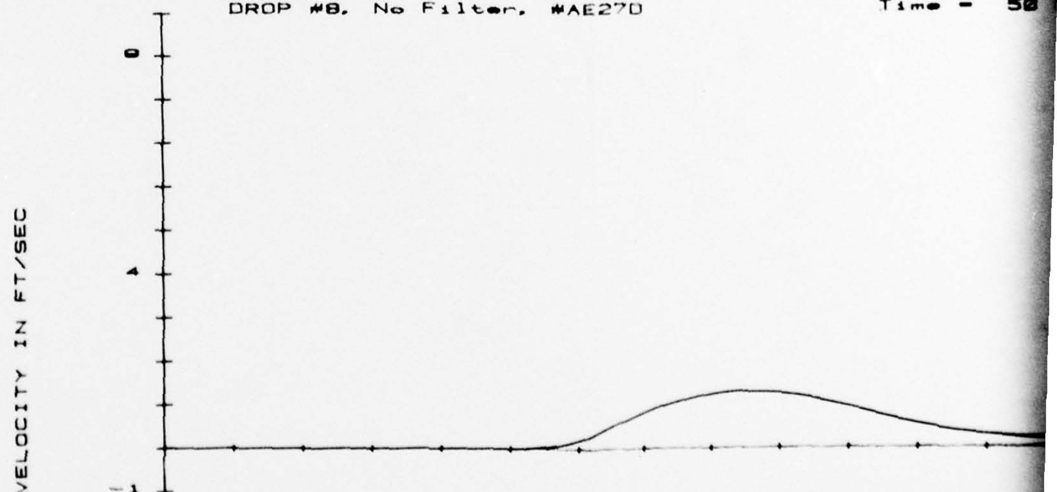

VERAL LAYERS OF TAPE WERE PLACED

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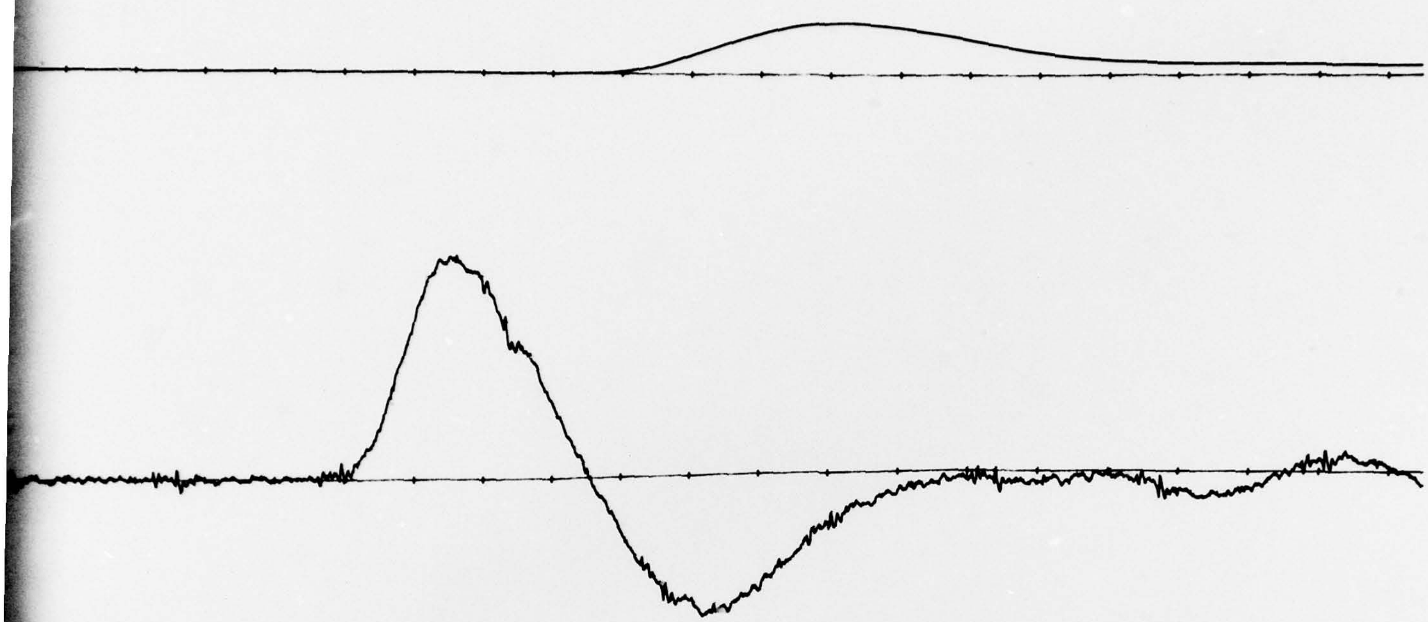

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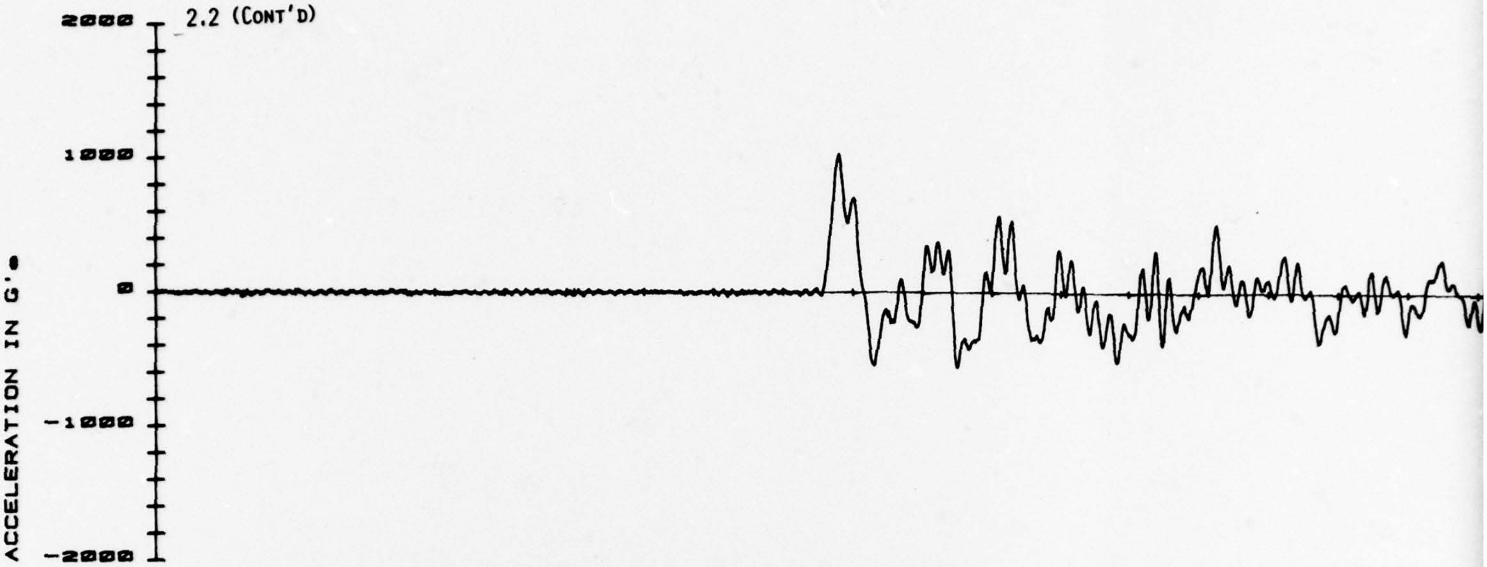

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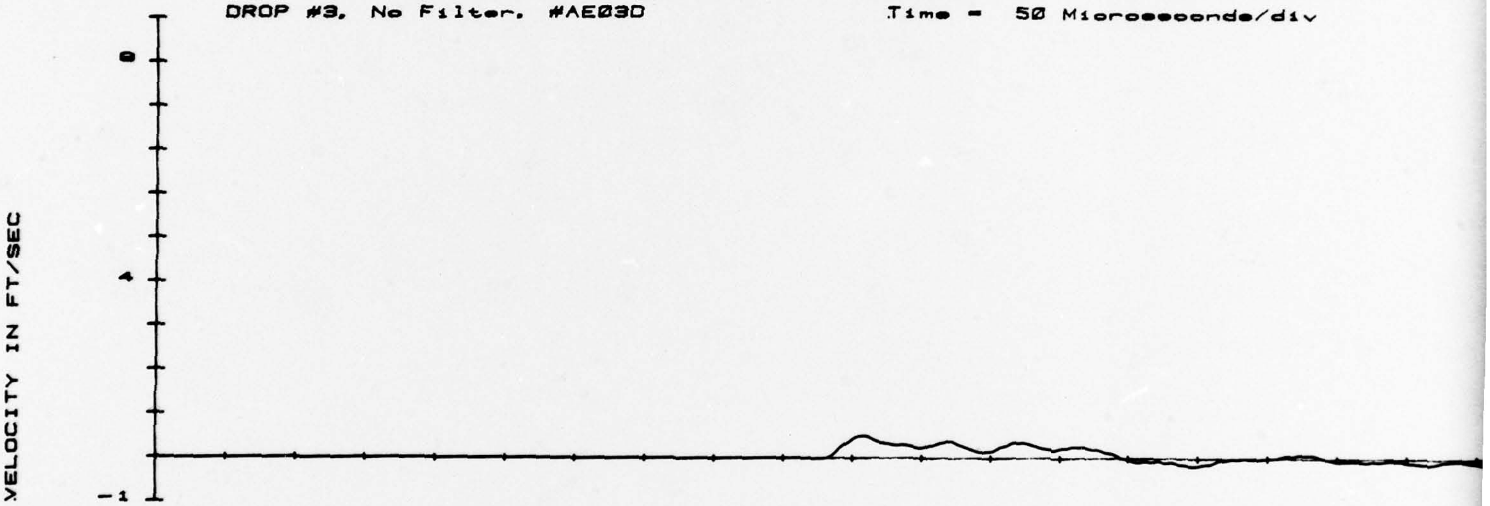

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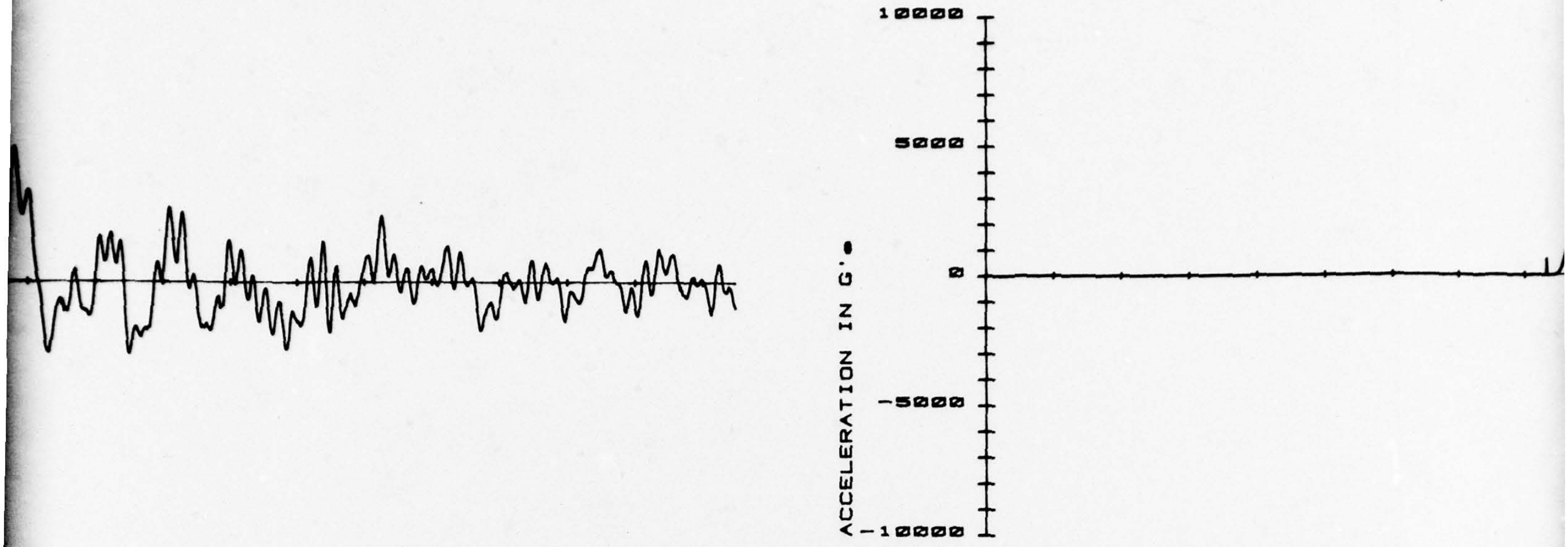

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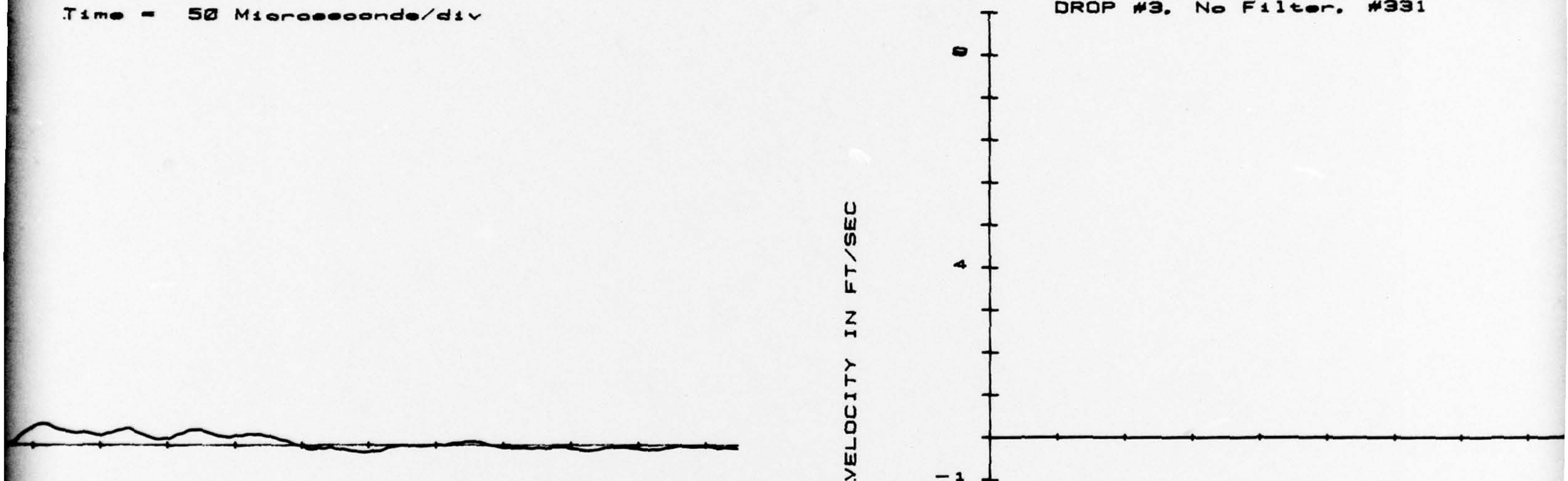

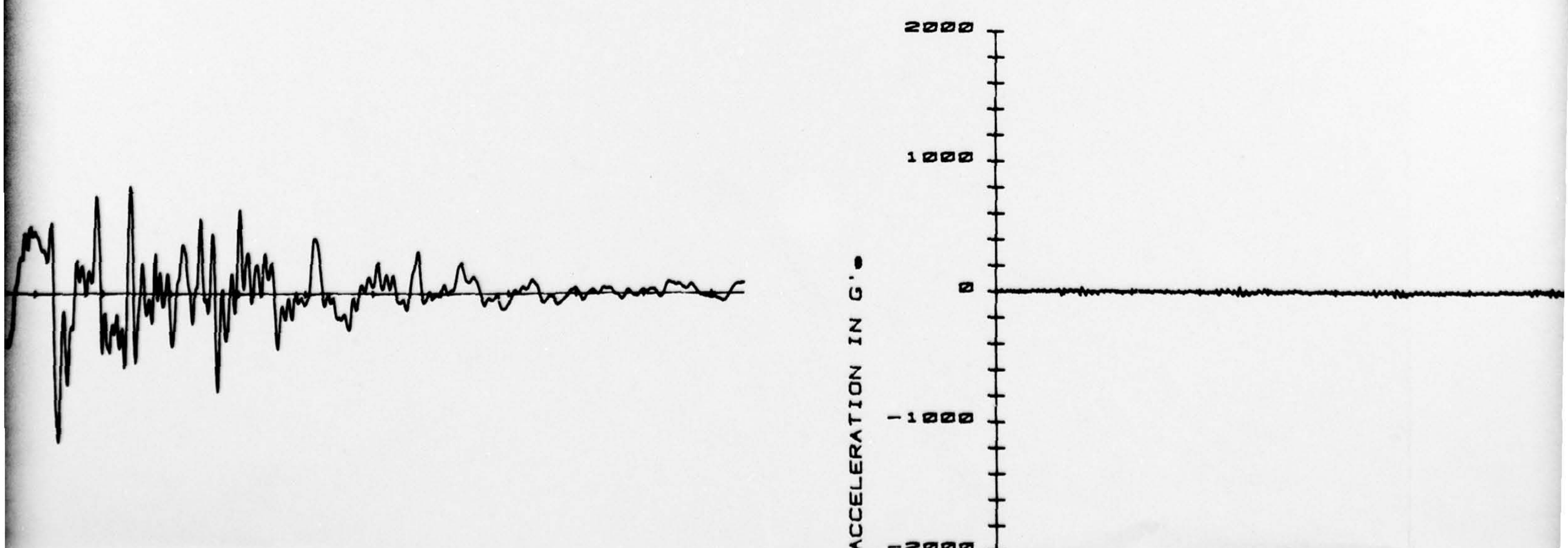

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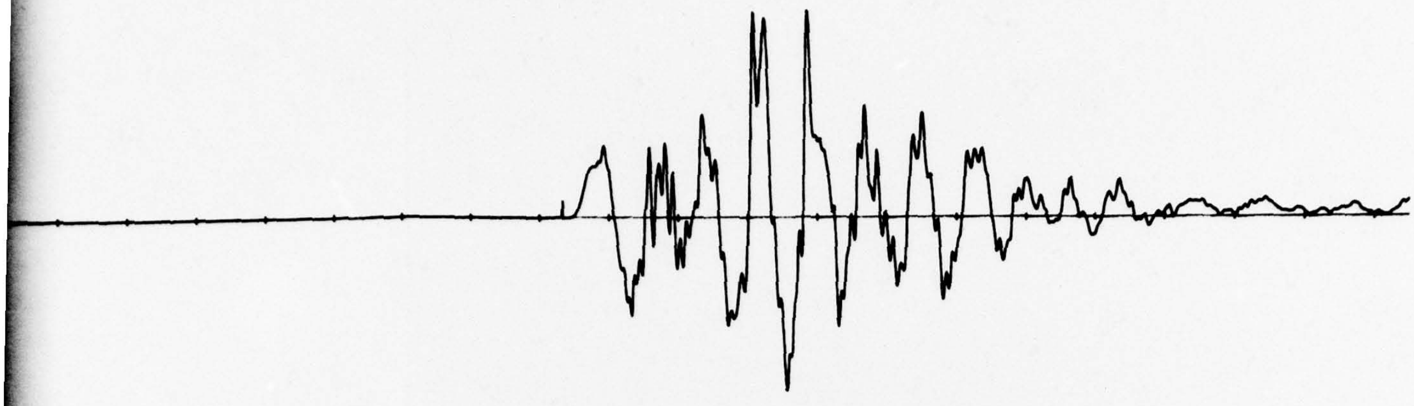

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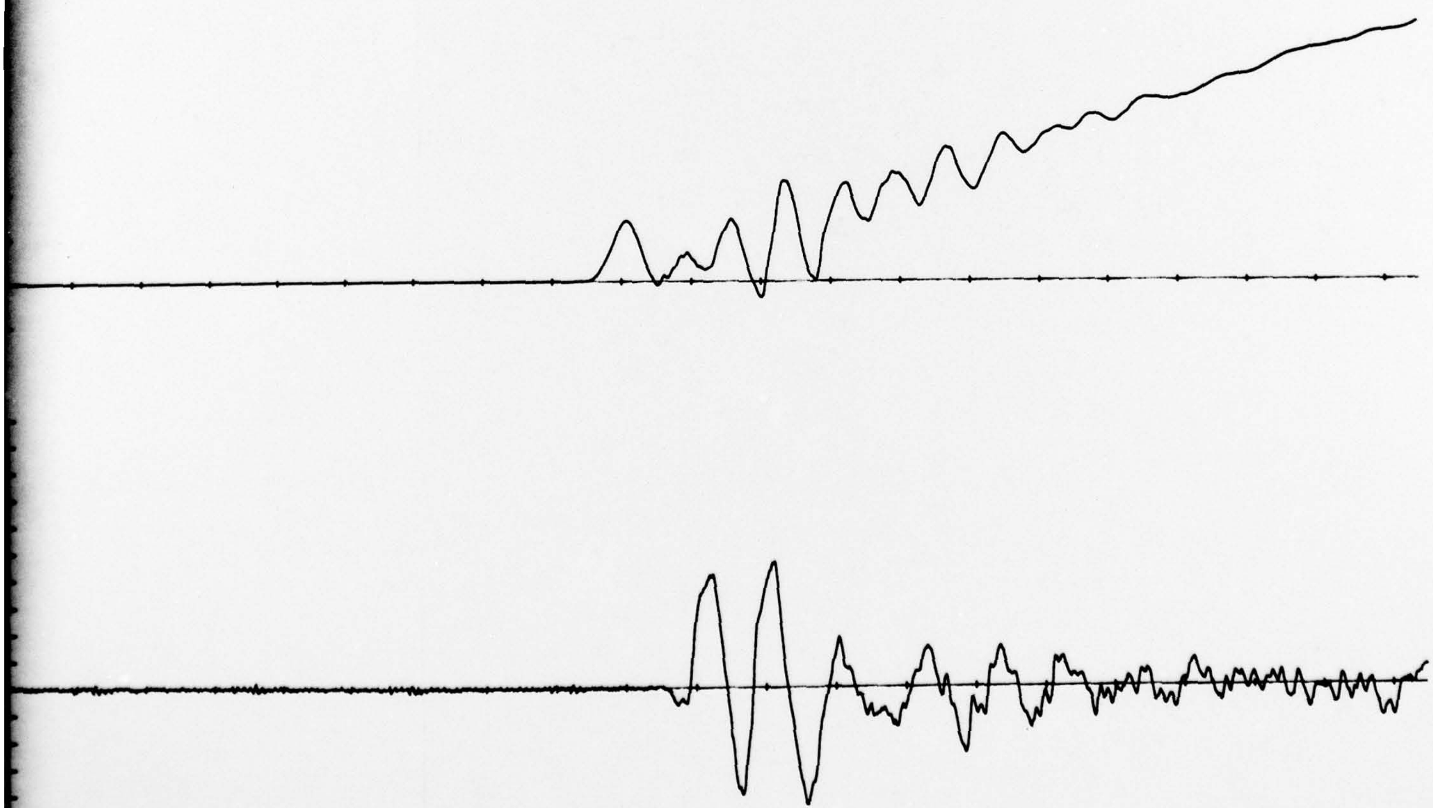

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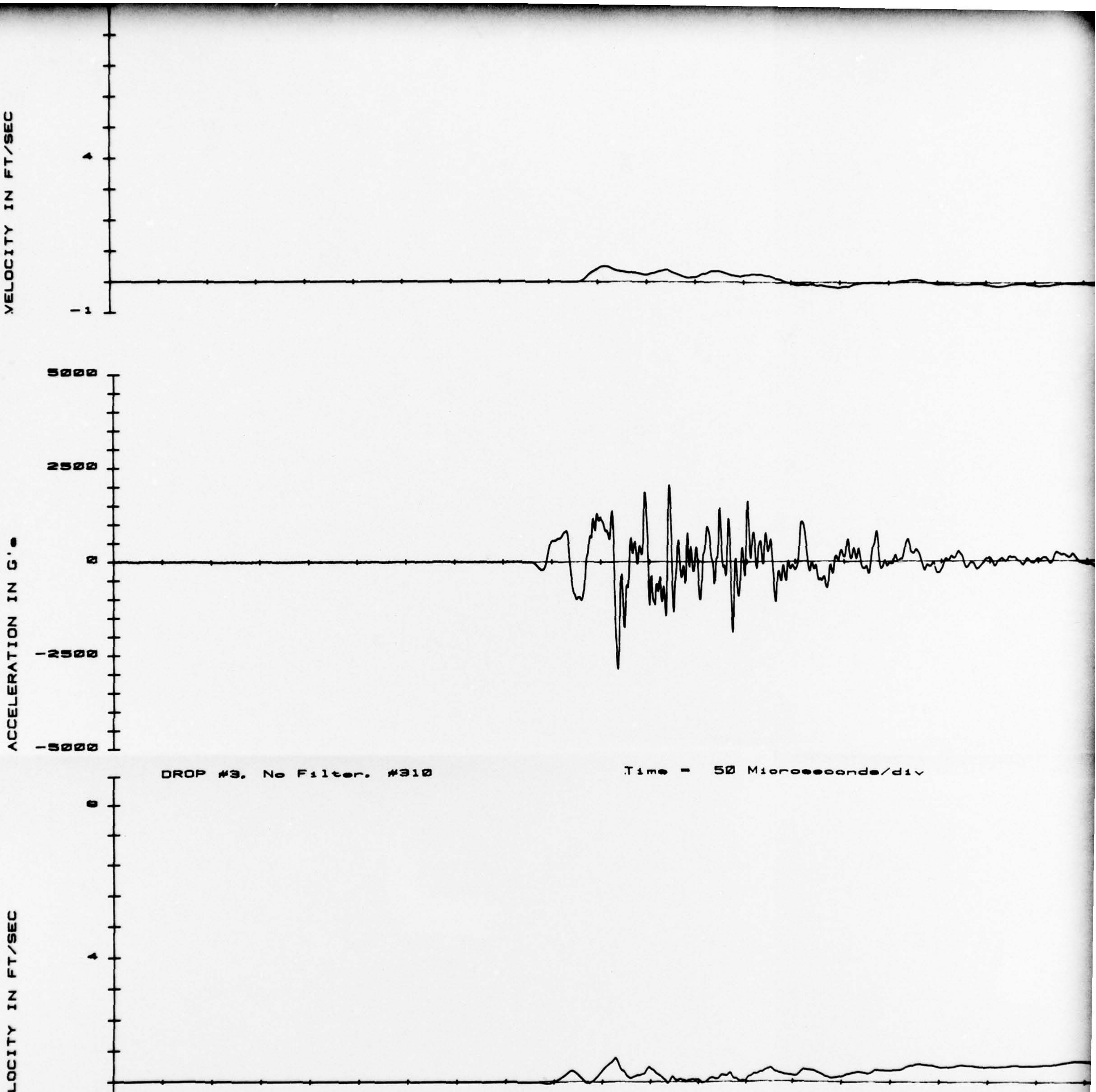
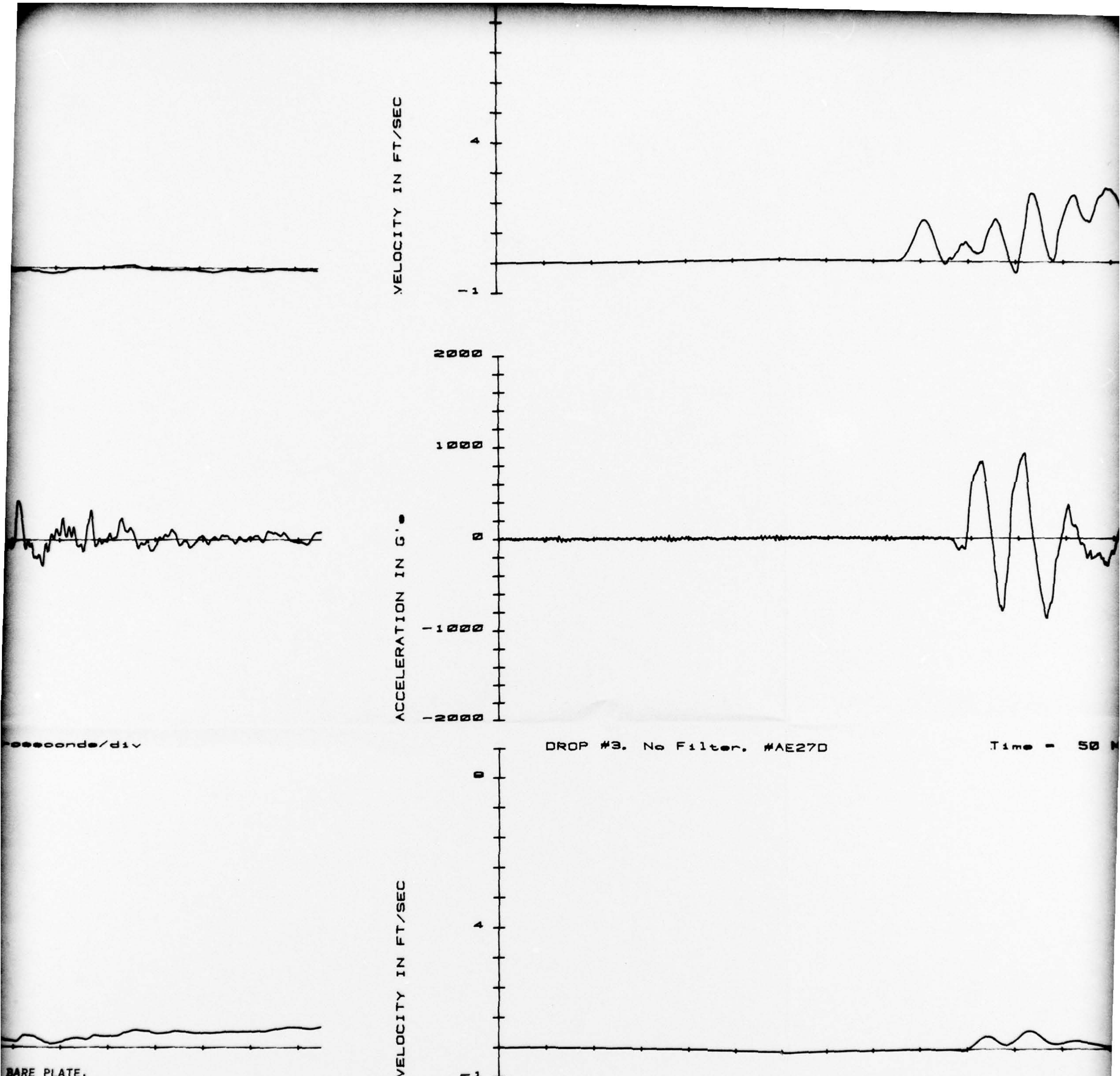


FIGURE 2.2-10. RESPONSE OF ACCELEROMETERS TO IMPACT OF A BALL BEARING ON BARE PLATE.



BARE PLATE.

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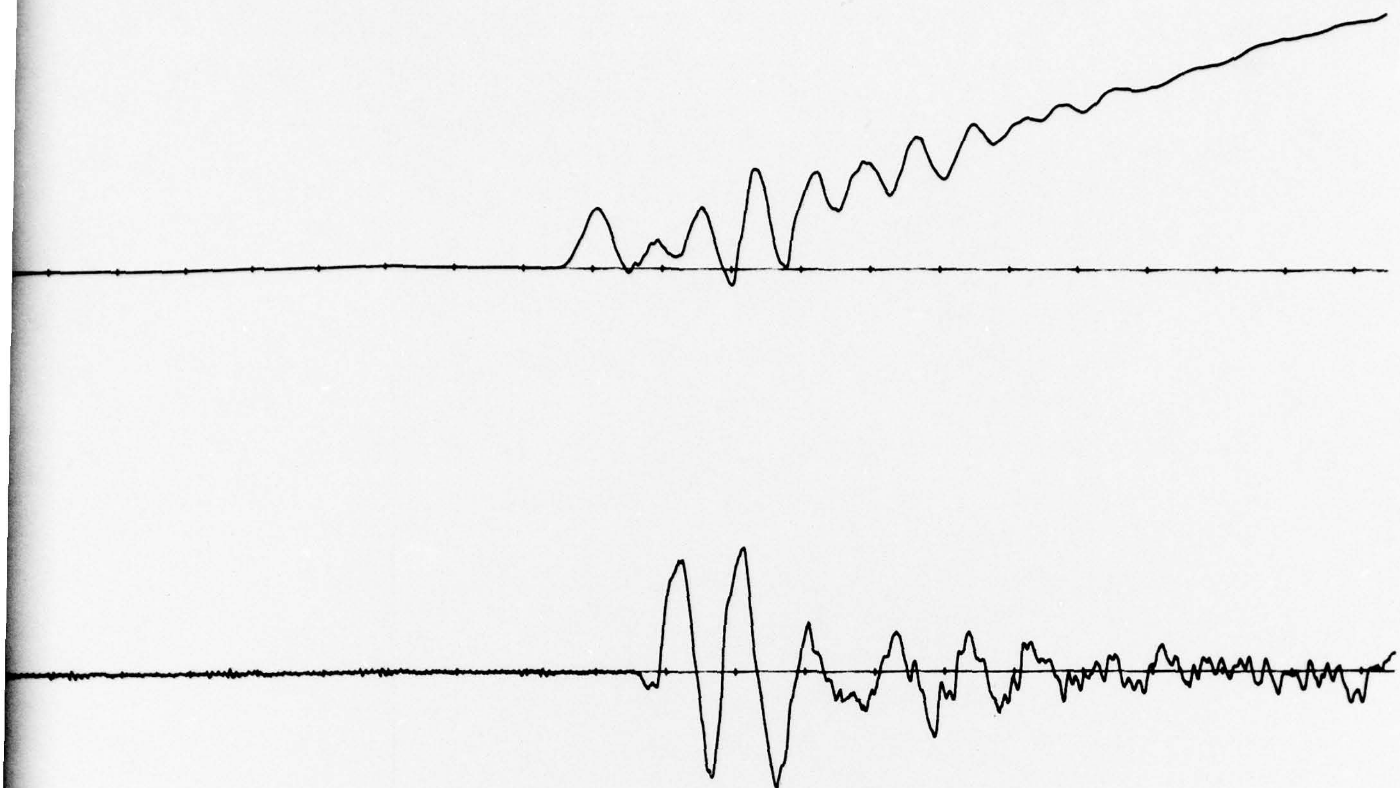

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